RESOURCE INTENSITY TRENDS OF FERROCHROME PRODUCTION IN SOUTH AFRICA

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Submitted for examination November 2019

Final version October 2020

A dissertation submitted to the University of Cape Town in partial fulfilment of the requirements for the degree of Master of Philosophy in Sustainable Development of Mineral Resources in the Department of Chemical Engineering

minerals to metals

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ABSTRACT

South Africa owns more than 70% of the world's known chromite reserves. Chromite has historically been the most feasible source of chromium suitable for ferrochrome production, which in turn is an essential raw material for stainless steel production. Stainless steel has a myriad of applications in modern society.

The South African ferrochrome industry was developed on the foundation of abundant raw material; historically cheap electricity and labour; and investment into industry research and infrastructure. The industry, like other mineral industries, has made a significant contribution to the socio-economic development of South Africa.

The South African government, through the Department of Mineral Resources, has drafted a mineral beneficiation strategy that is focused on developing the downstream industry to leverage the abundant mineral resource for prolonged and increased benefit to the South Africa. Yet while the ferrochrome and stainless-steel value chains have been identified as strategic, their mining and processing is resource intensive and a significant contributor to emissions that have the potential of causing environmental degradation.

In order to have meaningful engagement between stakeholders, there must be reliable information. This has resulted in the development of sustainability indicators to facilitate engagement. Of the various types of sustainability indicators, resource intensity, which is the ratio of the resource used to the unit product, was selected for this study. This was because resource intensity trends can be used to show the effects of environmental constraints quantitatively and qualitatively, such as ore grade and the effects of technological innovation on processing a mineral resource. In this way, decisions can be made regarding the environmental impacts and the technology required to mitigate these.

From a review of similar studies, it was found that approach for a similar included gathering data from mining company reports and, where possible, collaborating with companies. These data were then compiled to identify trends showing whether industries have improved in certain aspects. The causes of those variations were also reported in conjunction with the trends. In certain instances, expert insights were used to support the investigations.

Most studies found that ore grades gradually decline, which increases input into the industry. However, technology improvements and improved process improvements have the potential to mitigate the effects of these declining ore grades. This observation informed the development of the hypothesis for this study, which is that process and technology improvements could avert an increase in resource input when an ore grade declines.

The methodology adopted for this study included compiling resource intensity trends from publicly available sources over the period 2007-2017 (and on one occasion data were shared by a ferrochrome producing company), mapping major industry projects over this period, and conducting interviews with eight industry experts to verify trends and establish the impact of technology choice in relation to observed resource intensity trends. It was assumed that the quality of the data was uniform and of a sufficiently high quality for comparison and analysis.

Although ore grade trends could not be obtained, it was inferred that ore grade is decreasing. This is due to increased usage of Upper Group 2 (UG2) seam chromium concentrate, which has a lower grade than the conventional higher ore grade, Lower Group 6 (LG6), or Middle Group 1 and 2 (MG1/2) seam ore. Moreover, the chrome source raw material quality used in ferrochrome production was found to be improving with the advent of pelletising and sintering technology, which makes it possible to use UG2 ore. This technology increases the durability of the ore, which also improves the efficiencies.

This has led to the development of industrial symbiosis, whereby platinum group metal (PGM) producers generate UG2 tailings, which are sent to co-located ferrochrome producers to produce chromium concentrate. Chromium concentrate forms part of the raw material to produce sintered pellets which are used to produce ferrochrome.

Electricity intensity was also observed to decrease over time due to improvements in process energy integration. The increased application of closed furnaces allows the use of flue gas from smelting for combustion to generate electricity and heat transfer of the hot gas to be used to heat up other process streams. The addition of a pre-reduction increased energy efficiency, in addition to improving ore efficiencies, collectively reduced the electricity requirements. Furthermore, the increased use of chrome sintered pellets has contributed to the decline in electricity intensity.

Water intensity trends could not be conclusively determined due to evolving water accounting. It was inferred that if the water accounting remained constant from when it was reported to change, the water intensity was also decreasing. This has been attributed to increased water efficiency investments such as increased paving of water canals to increase recycling.

Reductant intensities could not be confirmed as there were insufficient data to draw the trends and consequently review them. It was mentioned that new Glencore proprietary furnace technology has reduced the requirement of expensive coke reductant.

The impetus of most of these projects was remaining profitable. The continual increase in the price of electricity in South Africa has propelled ferrochrome producers to reduce their electricity usage, as electricity accounts for up to 50% of ferrochrome production costs (Pan, 2013).

Legal compliance has also motivated some technology implementations. For instance, in preparation for the carbon tax, manufacturers reduced their electricity use and started to increase the combustion of carbon monoxide off-gas from smelting for electricity production and other applications such as heat integration and pre-reduction.

There has also been an increase in awareness of climate change and greenhouse gases, and the need for more responsible and sustainable mineral processing. The public perception of a company can significantly affect its profitability, with environmental protests affecting operations and consequently profits.

ACKNOWLEDGEMENTS

I thank God for all His grace, guidance and strength during the journey of compiling this dissertation and completing the MPhil programme.

To my supervisor, Prof. Harro von Blottnitz, I am very grateful for the opportunity to pursue the Mphil programme and for the opportunity to learn from you. Thank you for your patience and guidance through this entire time. I am grateful for all your efforts in ensuring that I always funded. You have also enabled me to develop professionally and at times reaching out to your professional network to support this dissertation, thank you for that. I am blessed to have worked with you. *Ich danke inhen*.

I would also like to extend my appreciation to Prof. Jenny Broadhurst, Dr. Valentina Russo and Dr. Edson Charikinya for your contributions towards this study.

I am grateful to the participants who freely supported this study with their time and knowledge. Without your input, I would not have been able to complete this study.

I would like to thank my family, particularly my mother, sister and father, for allowing me to pursue my post graduate studies. I appreciate the encouragement and all the support you gave me. I can never thank you enough. *Ngiyabonga boNkhosi*.

To my friends and colleagues; we had some great moments learning from each other and supporting each other. I appreciate you. Special thanks to Mixo Ngwenya, David Viljoen, Mvano Mgam, De Waal Hugo, Lelia Lelia, Bonolo Skee and Alexandra Himunchul.

I wish to acknowledge the funding from Minerals to Metals in the Department of Chemical Engineering and funding from the Department of Mechanical Engineering. I also thank you for the contributions towards my personal development.

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GLOSSARY

BIC	Bushveld Igneous Complex
EiRC	Ethics in Research Committee
FeCr	Ferrochrome
GHG	Greenhouse Gas emissions
GRI	Global Reporting Initiative
ICDA	International Chromium Development Association
IIED	International Institute of Environment and Development
IFML	International Ferro Metals Limited
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LG6	Lower Group 6 seam of the BIC
MG1/2	Middle Group 1 and 2 seams of the BIC
PGM	Platinum Group Metal
SDG	Sustainable Development Goal
UG6	Upper Group 6 seam of the BIC
UN	United Nations
WCED	World Commission on Environment and Development

1. INTRODUCTION

1.1 Background

Ferrochrome is an alloy which is mostly used in the manufacturing of stainless steel. Stainless steel, like other mineral resources, is a raw material that is used to produce numerous products which have become crucial to modern human life because of their vast applications.

South Africa owns approximately 74% of the world's known viable chromite reserves, and up to 80% if Upper Group 2 (UG2) seam's reserves are included (Pan, 2013, p. 106). Chromite has historically been the only viable source of chromium used to manufacture ferrochrome through carbothermic pyrometallurgical processing. Approximately 90% of ferrochrome produced is directed towards stainless steel production; around 180 kg of ferrochrome is required as input to manufacture a tonne of austenitic stainless steel (Johnson, et al., 2008, p. 186).

Over the last 30 years, the South African ferrochrome industry has established itself to be one of the leading global producers. This was based on enabling factors, such as abundant raw material, the availability of cheap electrical energy at the time, technology and infrastructure (Barcza, et al., 1995; Basson, et al., 2007). Production capacity reached over four million tonnes by early 2007 (Basson, et al., 2007), and in 2013, South Africa produced 34% of global ferrochrome production (Pan, 2013). In 2016, 54% of South Africa's chromium sales were exports, with over 15,000 people being employed in the industry.

The South African government regards the mineral industry as a means of development, whereby the industry can contribute to the country's socio-economic goals (Bhengu, 2015). With an estimated USD 6.2 trillion worth of mineral resources in South Africa, the government has adopted a mineral processing-based strategy to harness the potential benefit from her minerals (DMR, 2011).

As a development strategy, beneficiation can be described as a policy aimed at adding value to unprocessed or partially processed mineral resources by developing the mineral value chain prior to export (Hausmann, et al., 2008). This is done with the aim of maximising the value of minerals. The chromium and stainless steel value chains have been identified as two of the key foci of the South African government's mineral processing strategy (DMR, 2011).

Whilst several benefits are associated with the minerals industry, there are also a myriad of sustainable development challenges that arise from mineral extraction and processing, such as negative social and environmental externalities (Azapagic, 2004, p. 639). It is also worth noting that beneficiation as a development strategy for countries with considerable mineral resources has been challenged. Hausmann et al. (2008) highlighted that beneficiation is commonly favoured largely based on anecdotal evidence and logic lacking empirical systematic analysis. Mudd (2007b) also pointed out that within the discourse on the sustainability of the mineral industry, there is a lack of information regarding the environmental impacts of mineral processing.

It has been proposed that a systematic analysis of a country's resources and capabilities would yield more fruitful results in the interest of development (Hausmann, et al., 2008). This type of analysis pertains to the evaluation of trade-offs between environmental, social and techno-economic objectives for development decision-making. These trade-offs can include the quantifiable effects of mining such as environmental impacts, technological requirements and socio-economic effects, which can be instrumental in decision-making regarding whether to exploit the mineral and the technological route.

Sustainability indicators can be used to carry out systematic analyses, systematic analyses can thus provide relevant information upon which meaningful discussions can be had and decision made (Mudd, 2007a; Hausmann, et al., 2008).

It has been suggested that sustainable development practices must be adopted to ensure the cohesion of social, environmental and economic goals of the country (DMR, 2017). In the context of mineral resources, sustainable development is framed to describe mining activities that promote environmental and socio-economic wellbeing during mining and post the life of a mine (Azapagic, 2004; Mudd, 2007). To that end, sustainability indicators can be used to assess whether mining and the technological requirements for managing costs can be employed sustainably.

The environmental impact per unit of metal produced has been used as a sustainability indicator for other mineral and metal industries in conjunction with qualitatively assessing the influences of technology and processing routes costs. Mineral industries include platinum group metals (PGM) (Glaister & Mudd, 2010), copper (Northey, et al., 2013) and rare earth metals (Haque, et al., 2014). Mudd (2007a) has referred to the environmental impact or requirement per unit of metal produced as resource intensity.

Historical knowledge of resource intensity trends, as well as the influences of those trends, can be used for decision-making, with the aim of sustaining the benefits of the minerals industry whilst mitigating the challenges associated with mineral resource development (Azapagic, 2004; Mudd, 2007a; Laurence, 2011).

1.2 Problem statement

South Africa owns a significant share of the world's chromite reserves, which is a key raw material for stainless steel production and has socio-economic relevance to South

Africa. The South African government aims to add more value to this mineral resource through beneficiation, thus a systematic analysis of the industry can provide more reliable information to inform such plans. Furthermore, the negative impacts of mining and mineral processing are considered lacking in the mineral development discourse. This includes the environmental impacts and the technology required to develop the industry. Sustainability indicators can thus be used to facilitate the systematic analysis of the industry for meaningful discussion and decision-making based on relevant information. Resource intensity trends have been shown to be a useful tool in the systematic analysis of metal industries, but none have been presented and studied thus far for the South African ferrochrome industry.

1.3 Objectives and scope

Accordingly, this study aims to systematically investigate the environmental impact of producing ferrochrome in South Africa using resource intensity trends. It further aims to determine the drivers of the variations in the resource intensity trends, particularly regarding the technology employed and variations in manufacturing routes.

To investigate the environmental impact of ferrochrome production in South Africa, the researcher conducted a literature review on the South African ferrochrome industry and presents the resource intensity trends for the industry. Equation I shows the calculation for calculating resource intensity for a given year represented by *i*.

$$Resource\ intensity_i = \frac{Quantity\ of\ resource\ consumed_i}{total\ ferrochrome\ produced_i}$$

Equation I

Resource intensity trends were compiled for the years 2007 to 2017 where data were available. These trends were based on South African ferrochrome producers published data and data that were shared with the study. The technological advancements and processing routes that these producers undertake were assessed for the effect on the trends, after which the drivers of those changes were investigated.

1.4 Dissertation overview

The literature review presented in chapter 2 begins by relaying the background and significance of the South African ferrochrome industry to South Africa and the world. This is followed by a description of ferrochrome production routes in South Africa to establish an understanding of the technology and resources required to produce ferrochrome. Subsequently, challenges faced by the South African mining industry and particularly ferrochromium production are reviewed. Moreover, sustainable development as a framework to address some of these challenges is discussed, at which point resource intensity is presented as a tool to investigate an aspect of sustainable development implementation in the industry. Previous studies are reviewed to guide this study. Chapter 3 introduces the methodology used, as well as the hypothesis, the research questions and the chosen method for conducting the study. The resource intensity trends are then analysed together with the outcomes of the interviews pertaining to the trends and their drivers in Chapter 4. In addition, a discussion concerning the results in relation to the research questions is presented. Lastly, Chapter 5 discusses the outcome of the study, with conclusions in relation to the objectives, key questions, hypothesis and recommendations.

2. LITERATURE REVIEW

This section details the background of the South African ferrochrome (FeCr) industry and its relevance locally and to the world. The development of the industry in South Africa is then discussed, followed by a description of common production methods. A review of the plan by the South African government to develop the stainless-steel industry follows, before a discussion on the sustainability of mineral resource development is presented. Lastly, resource intensity is discussed as a systematic approach to analysing the industry and previous similar studies are reviewed.

2.1 Background and significance of ferrochrome to South Africa

Ferrochrome (FeCr) is an alloy that is primarily constituted of 50-70% chromium (Cr), iron (Fe) and a small amount of carbon (C) and silicon (Si). Chromium is a light grey lustrous element with considerable inert qualities, making it suitable for coating other metals, rendering them less susceptible to corrosion (Neizel, et al., 2010). Ferrochrome is thus a crucial raw material in the production of stainless steel and other special alloy steels (Basson & Daavittila, 2013).

Approximately 90% of all processed chromite is used in different grades of ferrochrome, which is used in the manufacture of stainless steel (Daavittila & Honkaniemi, 2004). Stainless steel, as a material of construction, has extensive applications in modern society (Neizel, et al., 2010). Typical applications include household catering utensils, medical apparatus, architectural and structural construction materials, and reactor vessels for the chemical industry (Johnson, et al., 2008).

Chromite (chromium ore) has conventionally been the only commercially feasible source of chromium (Neizel, et al., 2010). The United States Geological Survey estimated the world’s chromite reserves to be 12 billion tonnes worth of shipping grade ore (Basson, et al., 2007), of which South Africa owns between 72% (over 11700 Mt) and 80% (if UG2 ores are factored) (Cramer, et al., 2004).

The South African ferrochrome industry has established itself to be a globally competitive producer, which withstood long periods of political and economic isolation prior to 1994. The industry’s development was based on the abundance of raw material (chromite ore), the availability of cheap electrical energy at the time, the availability of human resources, and the development of required technology and infrastructure (Barcza, et al., 1995; Basson, et al., 2007).

Predating 2007, the industry underwent significant ownership changes because of international investments, which were regarded as a reflection of the good investment potential of the industry in South Africa at the time (Basson, et al., 2007).

By early 2007, South Africa's ferrochrome production capacity reached nearly 4.2 million tonnes, which included feedstock to refined products and reclaimed alloys from slag dumps (Basson, et al., 2007). In 2013, South Africa accounted for 34% of global ferrochrome production (Pan, 2013), with 54% of chromium sales being exports in 2016. The South African chrome industry employed over 15,000 people in 2016, with the entire South African mining industry contributing an average of 8% to the country's Gross Domestic Product between 2006 and in 2016 (Chamber of Mines of South Africa, 2017).

Mining has been a major economic driver in South Africa, which has shaped the socio-economic and political development of the country (Bhengu, 2015; DMR, 2017). Infrastructure and manufacturing have developed due to investments in mineral resources (Bhengu, 2015), including economic infrastructure which has led to the development of secondary and tertiary infrastructure (DMR, 2017).

Despite the abundant chromite reserves and the promising industry, South Africa's ferrochrome industry has become less competitive, resulting in a decline of South Africa's market share to the second largest ferrochrome producer over the last decade. This has been collectively attributed to increasingly high energy and labour costs, and inadequate infrastructure development (Bhengu, 2015).

The contribution of mining towards South Africa's GDP has also begun to decline since gold production started to decrease, however mining still provides employment and foreign exchange earnings, and supports other economic activities which are beneficial to South Africa. This decline in the mining industry is hoped to be offset through increased downstream beneficiation (DMR, 2017).

The Department of Mineral Resources (DMR) compiled the Mineral Beneficiation Strategy to leverage the country's abundant mineral reserves, with the goal of promoting a competitive minerals industry and developing a downstream mineral value chain aligned to other development programmes. Amongst others, stainless steel has been identified as a potential strategic value chain, which is to be supported by, amongst other measures, ensuring the availability of raw material such as chromium (DMR, 2011).

Mineral beneficiation is considered to be a development instrument, which was officially adopted by the South African government as a development strategy. In 1994, the ANC government, which was the first democratically elected government of South Africa, committed to creating a better life for all South Africans. The benefits of mining are aimed at rural development through employment and contributing to socio-economic programmes (Bhengu, 2015).

Hausmann et al. (2008) stated that although localised beneficiation has the benefits of reduced costs, more secure and cheaper supplies, and the potential to meet specialised downstream producer needs, the choice to purse localised beneficiation is often based on anecdotal evidence and flawed logic, and not a systematic empirical analysis. Mudd (2007a) also noted a lack of sustainability data in the discourse surrounding mineral resource development.

It has been proposed that for the mining industry to stay relevant, sustainable mining practices with regards to social and environmental wellbeing should be emphasised. In addition, mining sustainably should encompass the “sustainable and integrated management of natural resources as well as prudent environmental systems” (DMR, 2017).

This requires an understanding of the various apsects of mineral resources, ore grades, geological constraints, environmental and socio-economic concerns, and the necessary technological requirements, to ensure that any development is sustainable (Mudd, 2007a).

South Africa is thus faced with the challenge of developing the ferrochrome industry to cater for several needs that are essential to the country’s development, while doing so in a manner that is sustainable. Accordingly, this study set out to investigate the geological constraints and technological requirements for the ferrochrome industry.

2.2 Process description and known resource intensity parameters, process routes

The preceding section established the relevance of the ferrochrome industry and the need to manage the sustainable development of the minerals industry, including the environmental impact of the ferrochrome industry. Accordingly, ferrochrome production processes are discussed in this section.

Ferrochrome production constitutes of mining, beneficiation, pelletising, sintering and smelting. Mining of chromium ore (chromite) can either be underground or open pit, depending on the region’s deposits (Gasik, 2013, p. 285; Mc Dougall, 2013, p. 83). Thereafter the chromite run-of-mine is treated through a comminution and size classification through crushing, screening and gravity separation in the beneficiation step. (Mc Dougall, 2013). Beneficiation produces concentrated which be fine or lumpy (Mc Dougall, 2013, p. 84). If the concentrate material is lumpy, it can be refined in a pyrometallurgical carbothermic reduction of chromite. Fine concentrate necessitates a pelletising and sintering prior to smelting.

The main raw materials in ferrochrome are fluxes, reductants and chromite (chromium ore). Most ferrochrome producers in South Africa are in the Bushveld Igneous Complex (BIC), where mining and smelting operations are integrated. Economically viable chromite in South Africa is only sourced from the BIC, which is characterised by funnel shaped intrusions from Doornvlei in the North West Province to Steelpoort in the Mpumalanga Province (Pan, 2013, p. 106). In addition, the BIC is expansive as it covers 400 km from east to west, and approximately the same distance from north to south (Neizel, et al., 2010). A stratigraphy of the BIC is shown in Figure 2-1.

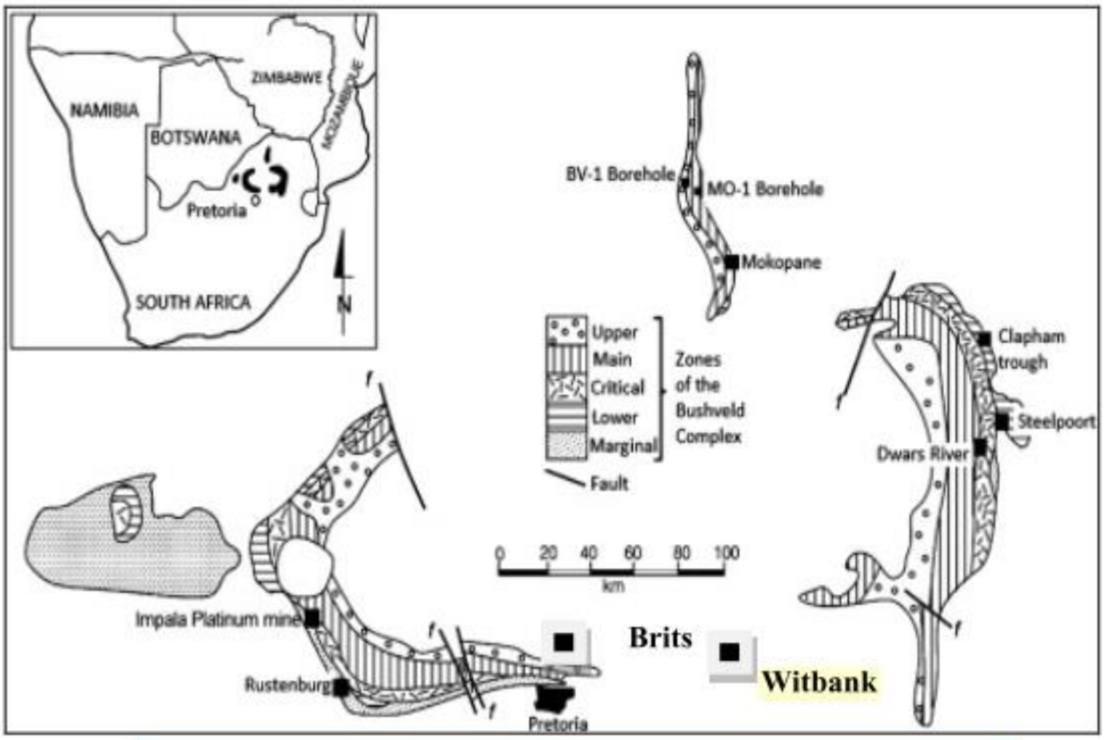

Figure 2-1: Stratigraphy of the Bushveld Igneous Complex in South Africa, oriented from Doornvlei in the North West Province to Steelpoort in Mpumalanga Province (Pan, 2013, p. 106).

Within the BIC there are numerous seams of interest, but the Lower Group 6 (LG6), Middle Groups 1 and 2 (MG1/2) and Upper Group 2 (UG2) have been the most viable (Cramer, et al., 2004, p. 48).

South African chromite has low ratios of chromium to iron (less than 1.6) in comparison to regions such as Zimbabwe (greater than 2.6) and Russia (greater than 2.8) (Neizel, et al., 2010). It has been noted that high Cr:Fe ratios are associated with higher chromium (III) oxide (Cr_2O_3) concentrations (Farjadi & Azari, 2004). Consequently, South African chromite has low Cr_2O_3 grades (less than 45%), resulting in chromium concentrations of less than 55% in ferrochrome produced (Basson, et al., 2007, p. 8)

Iron is inherently present in chromite, which reduces more readily than chromium (Cr), such that nearly all the iron in chromite ends up in the ferrochrome product. Producers are only paid for the chromium content and not the iron, therefore high ratios of Cr:Fe are preferred for ferrochrome production (Neizel, et al., 2010, p. 11).

Chromite beneficiation processes depend on the characteristics of the ore. Some ore high grade ores only require hand sorting, lower grade ores require crushing and more rigours separation techniques. The crushing and screening as shown on Figure 2-2 liberates the chrome mineral from the gangue material. The reduced size also makes it is easier to manage in the subsequent concentration step by producing consistent grain size as this affects the recovery of the concentration section (Murthy, et al., 2011).

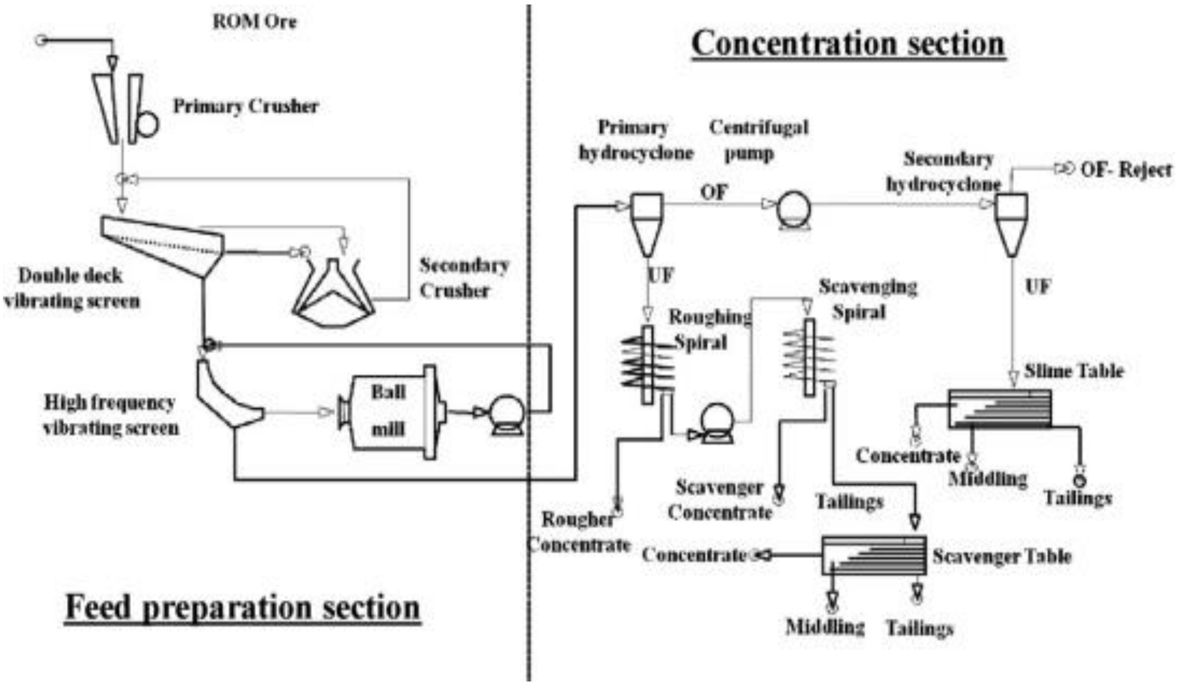

Figure 2-2: Chromite beneficiation (Murthy, et al., 2011)

Owing to the difference in densities between the gangue and chromium, gravity separation units such are hydrocyclone, spiral concentrators and thickeners as depicted in on Figure 2-2 in the concentration section. Runoff with a concentration of 20-30% can be concentrated to 45% using the process shown on Figure 2-2 (Murthy, et al., 2011). Depending on the minerology and ore characteristics; a combination of floatation circuits, magnetic separators and electrolysis separator can be used.

South African chromite is largely brittle, with varying proportions of fine ore and minimal lumpy ore (Basson & Daavittila, 2013, p. 329). Only 10-15% of South Africa's chromium ore is lumpy, whilst about 73-82% can be classified as fines. Lumpy ore is preferred for reduction because it prevents dangerous blowouts and bed turnovers in furnaces (Neizel, et al., 2010, p. 25).

Lumpy or agglomerated concentrated ore is often fed to larger, closed alternating current (AC) furnaces, whilst the concentrated fine ore fraction is smelted in smaller, open direct current (DC) furnaces (Basson & Daavittila, 2013, p. 320). As the industry has moved towards more closed furnaces due to environmental, and consequently profitability concerns, this has meant that concentrated fines ore must undergo some form of agglomeration before being charged into the furnace (Basson, et al., 2007, p. 8). The limited supply of lumpy ore has also given rise to the acceptance of UG2 chromite concentrate from the PGM industry as a viable source of chromium ore (Basson, et al., 2007).

Concentrated fines ore is usually agglomerated through briquetting, pelletising and sintering. Pelletising and sintering entail mixing fine chromite, carbon fuel source (e.g. coke) and binder (e.g. bentonite) at a specific moisture content, which is roasted at a high temperature to oxidise the iron with the aim of improving the quality of the pellet (Gasik, 2013, p. 287).

This is commonly done by mixing concentrated chromite ore and reductant with water in a ball mill. Thereafter the mixture is drained off water in a vacuum filter before a binder is added. This is then mixed and subsequently fed into a pelletising drum to form pellets, which are sintered/heated gradually to reduce moisture and allow the binder to form chemical bonds with the chromite. The heat energy may be sourced from the combustion of coke and gas burners, or alternatively from waste CO gas from furnaces (Mc Dougall, 2013, p. 129). Sintered pellets can then be fed into a pre-heater, pre-reduction kiln and furnace for smelting.

Briquetting entails the mixing of concentrated fine ore with a suitable binder in specified portions, which is then fed into a silo to be discharged into a double roll briquetting press, which produces briquettes that are cured for 24 to 48 hours. At this point the briquettes can be fed into a pre-reduction kiln, preheater or furnace, in the same way as sintered pellets (Mc Dougall, 2013, p. 128).

The success of agglomeration depends on the binder, which influences the cold and hot strength; cold strength is resistance to crumbing during handling, and hot strength is resistance to crumbling and chipping from an abrasive collision during smelting (Mc Dougall, 2013, p. 128).

The chromite (fine, agglomerated or lumpy), reductants and fluxing materials are stored on site to be fed into a furnace for smelting. The main chemical reactions that occur in the furnace are seen in Equation II and Equation III below.

Equation II (Neizel, et al., 2010, p. 25)

$$Cr_2O_3 + 3C \rightarrow 2\mathrm{Cr} + 3\mathrm{CO}$$

Equation III (Neizel, et al., 2010, p. 25)

$$FeO + C \rightarrow \mathrm{Fe} + CO$$

For mass composition of carbon exceeding 4%, ferrochrome products can be categorised as shown in Table 2-1 (ICDA, 2016).

Table 2-1: Ferrochrome products composition and country of production (ICDA, 2016)

FeCr Product	Cr%	C%	Si%	Countries
High grade High Carbon (HC) FeCr	65 – 72	≤ 10	≤ 2.5	Kazakhstan, Russia, Albania, Sweden
Low grade HC FeCr	47 – 65	≤ 10	≤ 4	China, India, Zimbabwe
Charge Chrome	45 – 57	4 – 8	2.5 – 7	South Africa, Finland, Brazil

Several furnace technology routes exist in the ferroalloy industry, with the selection of a route depending on the available raw materials, access to technology, electrical costs, and environmental and occupational health concerns (Basson & Daavittila, 2013). In addition, the recipe used, and consequently the specific ferrochrome product, may influence technology choice (Neizel, et al., 2010). These routes have been summarised in Table 2-2.

Table 2-2: Furnace technology routes (Basson & Daavittila, 2013, p. 332)

Technology route	Characteristics	Advantages	Disadvantages
Open or semi-open submerged AC	• <30 MVA • 70-75% Cr recovery • 4300 kWh/t	• Can operate with low quality feed • Low capital investment • Ease of operation	• Low thermal and metallurgical efficiencies
Closed submerged arc AC	• >135 MVA • 83-87% Cr recovery • 3200 kWh/t	• Carbon monoxide (CO) can be used • Higher metallurgical and thermal efficiencies • Low unit capital investment cost	• High quality ore and reductants are essential for operation

Technology route	Characteristics	Advantages	Disadvantages
Prereduction preceding closed submerged arc AC	60 MVA 88-92% Cr recovery 2400 kWh/t (Electrical energy only)	CO can be used High metallurgical and thermal efficiencies Low coke consumption Good environmental results	High capital cost (low capital cost per tonne produced)
Open DC	60 MVA 88-92% Cr recovery 4300 kWh/t	Can use low quality ore and reductant High metallurgical efficiencies Simplified furnace control	Lower thermal efficiency than pre-reduction closed submerged arc AC

Slag, carbon monoxide rich gas and ferrochrome are produced from the furnace. Carbon monoxide gas produced during smelting can be used to preheat feed into the furnace, as well as for sintering pellets. Due to the significant calorific value of CO, the gas can also be combusted for electricity production (Basson & Daavittila, 2013). By 2007, nine pelletising facilities and seven preheaters had been constructed in the South African ferrochrome industry, with more being planned. Furthermore, the generation of electricity from CO rich gas has been successfully implemented in Samancor's manganese operations (Basson, et al., 2007). Basson et al. (2007) reported at the time that many furnaces in South Africa were open or semi-closed, whilst Neizel et al. (2010) noted that all greenfield projects included a pelletising facility, which extended to include semi-closed furnaces.

Slag may contain significant ferrochrome content, which may be extracted in a metal recovery plant. A typical generic flow diagram of ferrochrome production is shown in Figure 2-3.

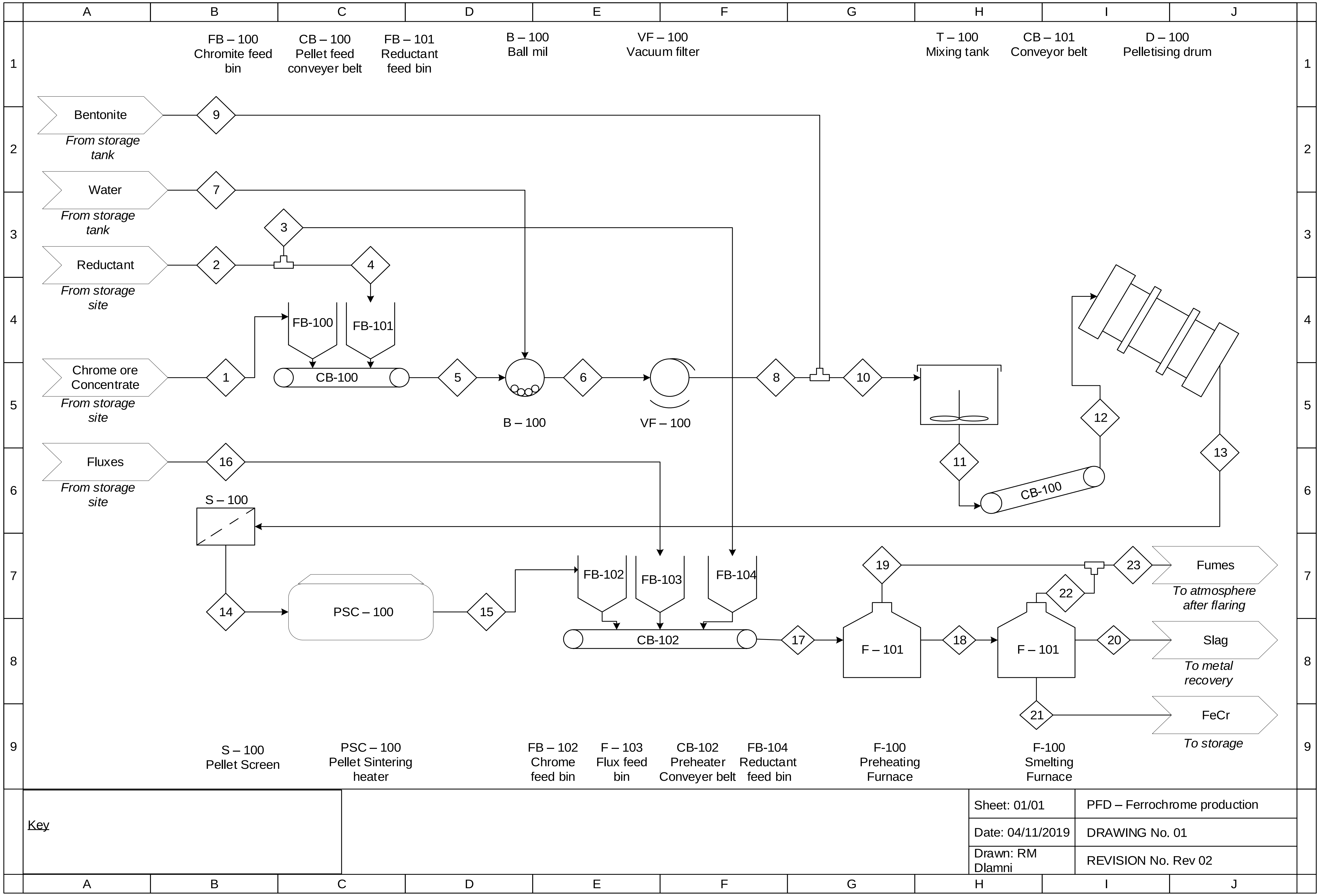

Figure 2-3: Process flow diagram of ferrochrome production

The access to technology, raw material, energy costs are noted to affect the choice of technology, the quantity of raw material, energy consumption, and accordingly the environmental impacts.

2.3 Sustainable Production

Mining and its products are associated with a myriad of challenges arising from social, environmental and economic dynamics (Azapagic, 2004). This is no different in South Africa. As discussed in section 2.1, this study is concerned with the sustainable development of the ferrochrome industry. This section thus reviews sustainable development theory in relation to mining.

2.3.1 Sustainable development

The conception of SD

The concept of sustainable development was conceived when it was realised that developed countries were accumulating more wealth and achieving higher standards of living, while developing countries were often left with increasing levels of poverty and a range of environmental issues (Mebratu, 1998). Moreover, the negligence of environmental and social considerations by multinational corporations resulted in unintended and undesirable consequences such as global warming, biodiversity loss and poverty. Multinational corporations were increasingly becoming difficult to manage for individual governments because governments had limited capacity and resources (IIED, 2002).

In 1987, following several efforts by groups such as the Club of Rome to address this problem, the World Commission on Environment and Development (WCED - commonly referred to as the ‘Brundtland Commission’) was sponsored by the United Nations to produce a report titled ‘Our common future’. Sustainable development was defined in the report as a framework to integrate and reconcile economic efficiency, social equity and environmental wellbeing (Mebratu, 1998). The definition states that:

“*Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (WCED, 1987, p. 37).

This description of sustainable development was designed to bring about consensus between developing and developed countries, civil society groups and corporations (IIED, 2002). The definition marked the first global consensus that economic growth can be achieved through goals that promote social well-being and environmental integrity (Laurence, 2011).

Criticism of definition and importance of the environment

Be that as it may, the report has been criticised for being too vague and open to interpretation (Hopwood, et al., 2005). Environmental proponents have criticised the report as being anthropogenically biased, because it could be interpreted to imply that limitless environmental exploitation was acceptable in the pursuit of fulfilling multi-generational human wants and needs (Hattingh, 2001). The notion of perpetual environmental exploitation stems from the perception that the three capitals (environment, economy and society) are independent of each other, as shown in Figure 2-4 (Hopwood, et al., 2005).

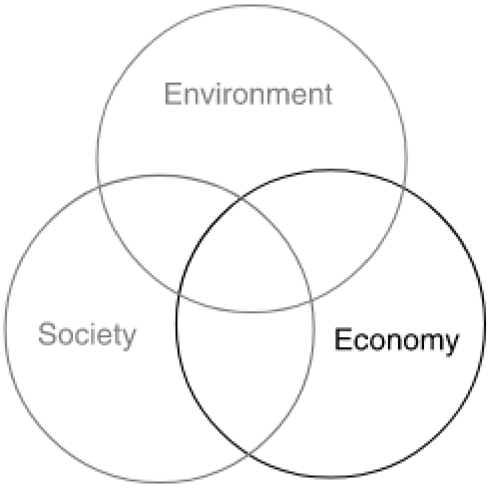

Figure 2-4: Common three-ring sector view of sustainable development (Giddings, et al., 2002)

In support of this viewpoint, the environmental is the foundation of human existence and that limits should be imposed on environmental exploitation to prevent irreversible and unpredictable changes to the natural environment, which may not be favourable to human survival (Hattingh, 2001). Therefore, environmental wellbeing and consequently limits are essential for society’s well-being, whilst the converse is not valid (Abdul Rashid, et al., 2008, p. 214). Figure 2-5 illustrates the view that the environment is indispensable because if forms the basis of the other capitals.

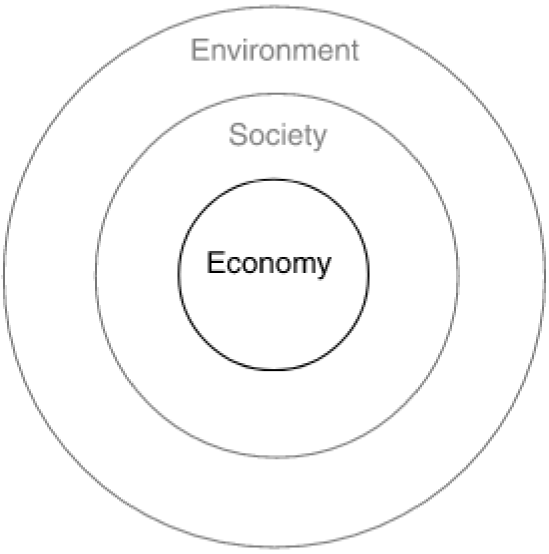

Figure 2-5: Sustainable development showing the economy dependent on society and both dependent on the environment (Giddings, et al., 2002).

This view about the environment gave impetus to governments, industries and other organisations to work towards practicing sustainable resource strategies in the interest of environmental preservation (Abdul Rashid, et al., 2008). This study focuses on the material and energy exchanges of the ferrochrome industry in South Africa, with the understanding that knowledge of these exchanges is essential to preserve the environment.

2.3.2 Resource efficiency and the minerals industry

The preceding section establishes the importance of preserving the environment to preserve human life. This is because human activity is changing ecosystems as the demand for food, fresh water, timber, minerals and fuel increases. These changes disrupt eco-system services leading to negative environmental changes and the risk of higher poverty levels for vulnerable groups (Ekins, et al., 2016). This means that whilst the mining industry has numerous benefits for human life and South Africa in general, the industry's activities also contributes to these eco-system changes. This section discusses mining with sustainable development considerations.

Views of Sustainable Development in mining

Laurence (2011, p. 278) stated that the concept of sustainable mining is contentious, because it is considered antithetical due to mineral resources eventually being depleted. It has been suggested that the contention regarding depletion is irrelevant because it is inevitable, i.e. it is argued that all other considerations around the sustainability of mining should be of high importance (Rajaram, et al., 2005). Laurence (2011, p. 279) added that mining can be sustainable if the “triple bottom line” is balanced, and if the benefits of mining last beyond the life of the mine. The triple bottom line refers to considerations of the economy, environment and society. This is important because mining has the potential to impact all the capitals (IIED, 2002).

The industry is a means of income and development for many countries (Azapagic, 2004; IIED, 2002). The role of mining managers is thus to make operations profitable and manage resources sustainably, however mining is a globally competitive industry and individual companies are unable to dictate commodity prices. The only option is therefore to manage the costs of an operation in order to remain profitable (Laurence, 2011). Whilst mining firms are expected to assume more responsibility, the international market pricing of commodities does not incorporate the implicit externalities that result from mining activities (IIED, 2002; Ekins, et al., 2016).

Mining activity invariably leads to several environmental impacts and the depletion of economic resources (Azapagic, 2004). Most of the energy used in the mining activities is sourced from fossil fuels which leads to CO2 emissions. Fossil fuel extraction and combustions is the largest contributor to anthropogenic climate change (Ekins, et al., 2016).

At times, mineral resources are depleted without value addition or adequate attention to negative environmental impacts. This deprives resource bearing countries of the full benefits of the resource, with the additional challenge of unmanaged environmental issues. Poorly managed mineral resources also have far reaching ramifications in the social sphere. For instance, poorly managed mining practices and inadequate accountability by the industry have yielded undesirable social and environmental legacies, leading to a loss of trust between companies, governments and civil society (IIED, 2002).

Way forward

Sustainable development has become a framework for identifying best practice (IIED, 2002). The framework is recognised in South African legislation, such as the Mineral and Petroleum Resources Development Act (MPRDA), as a guiding principle to ensure that the country’s mineral and petroleum resources are exploited with the aim of benefiting present and future generations. This includes a life-cycle approach management to mining to preserve the natural environment (Mineral and Petroleum Resource Development Act, No 28 of 2002. Regulation. 2013).

Sustainable Development Goal 12 is concerned with sustainable consumption and production, and with reference to mining constitutes incorporating sustainable mining practices into core business practices, as well as collaborating with stakeholders through reporting in order to facilitate engagement (Sonesson, et al., 2016, p. 51).

It has been suggested that mining is sustainable if it satisfies the triple bottom line (society, economy and environment). In addition to the three pillars of sustainable development, mines also need to incorporate safety and high efficiency extraction of value from the mineral resources (Laurence, 2011). This is illustrated in Figure 2-6.

Figure 2-6: Sustainable mining practices (Laurence, 2011)

Sonesson et al. (2016) mapped mining to the Sustainable Development Goals (SDGs), and noted that reducing process inputs such as water, energy, land, chemicals and other raw materials is a means by which mining can contribute to sustainable development. Ekins, et al. (2016) state that resource efficiency is crucial to protecting ecological systems and the services they provide. Spuerk et al. have also stated that resource efficiency is concerned with responsible consumption of natural resources (2017).

Spuerk et al. (2017) noted that in manufacturing, improvements in resource efficiency are associated with reducing material consumption which effectively reduces the impact on the natural environment further upstream in the value chain. Ekins et al. (2016) describes resources as elements of the physical world which can be used to provide goods and services.

Improved resource efficiency is also considered advantageous because of the direct economic efficiency as a result of cost savings from reduced product loss, less raw material consumption, and reduced water and energy consumption (Abdul Rashid, et al., 2008; Ekins, et al., 2016). The reduction in resource use not only promotes the resilience of the economy but also that of the natural environment through mitigating the environmental strain on the natural resources and reduction of negative environmental impact (Ekins, et al., 2016).

The mining industry is already benefiting from corporate sustainability practices such as reduced costs (e.g. lower labour health costs by providing safer working environments), improved company goodwill, and market advantages (IIED, 2002), through initiatives such as decoupling resource use from production. Managing resources efficiency is central to every sustainable manufacturing strategy (Abdul Rashid, et al., 2008). Increased environmental awareness has exerted pressure on manufacturing operations, both legally and societally, to reduce their environmental impacts through improved process efficiency and waste minimisation (Martins, et al., 2007).

The IIED (2002) stated that sustainable development in mining should entail continuously improving social, economic and environmental contributions. In practice this includes incorporating and developing sustainability performance indicators for measuring and monitoring, as well as continuous evaluations of these indicators (Azapagic, 2004). Therefore, resource efficiency targets need to be set and monitored. Achieving these targets requires incremental and large innovation driven increases (Ekins, et al., 2016).

Evaluating and monitoring also contributes to incorporating some of the implicit costs of mining operations, such as environmental degradation and the need for mitigation (IIED, 2002). These indicators to be meaningful enough to facilitate a collaborative relationship with stakeholders based on trust and respect (IIED, 2002).

It has been proposed that the continuous and collaborative assessment of resource efficiency in mining is crucial contribution for preserving ecosystem services and human wellbeing that mining activities affect. To achieve this, resource efficiency must be monitored.

2.3.3 Sustainability indicators

This section discuses sustainability indicators, particularly in relation to resource efficiency.

Sustainability indicators are developed with the intention of addressing sustainable development concerns. Selected indicators must therefore reflect the key sustainability concerns of the industry in question (Azapagic, 2004). For sustainability indicators to be accepted and meaningful, the calculation models must be reliable and robust (Wiedmann, 2009).

Environmental indicators had been the most developed of the three sustainability indicators some time back and have received the most consensus (Azapagic, 2004). Social and economic indicators were not investigated as part of this study. There are also integrated indicators, which have the advantage of being fewer in number and furthermore include the other aspects of sustainable development. These were not used as they extended beyond the scope of this project, however, and because there is little consensus about how and when they should be used (Azapagic, 2004).

As an environmental indicator, resource efficiency assesses the relationship between a system’s resource input and output. Measuring input using physical metrics against output in physical and economic metrics are established approaches (Spuerk, et al., 2017). Spuerk, et al. (2017) cautions against the use of financial or economic metrics due to the variability such as the market price changes.

Resource efficiency is commonly measured in terms of input and output ratios such as resource intensity (Spuerk, et al., 2017). Resource intensity was first proposed as material intensity per unit service in 1992 as an initial measure of resource efficiency of products and services (Abdul Rashid, et al., 2008, p. 220). Although not explicitly defined by Mudd (2007a) and Spuerk et al (2017), resource intensity was used to indicate the amount resource used to produce a unit of product. Resources were not exclusive to material but also included energy. Resource intensity was the chosen indicator for this study.

Indicators such as eco-efficiency were considered, however they were forgone because of the complexity (e.g. integrating economic-burden and environmental concerns) which were outside the scope of this study. In addition, other indicators such as waste minimisation and LCAs, which focus on waste and environmental impacts respectively, both contribute to resource efficiency, however the focus of this study was on inputs into production (Abdul Rashid, et al., 2008).

Water, land, materials and energy are well established intensities withing regards to resource intensities in mining (Spuerk, et al., 2017). Normalising indicators enable comparisons between companies of different sizes, especially when expressed per unit mass of product (Azapagic, 2004; Mudd, 2007a). Comparisons can be extended to different technologies and regions; hence normalised indicators were used in this study.

In the mining value chain, concentrated ore is usually the first product that can be sold into the market. A significant portion of the beneficiation occurs on the mine site, Therefore to account for the resources required for beneficiation, the system boundaries would have to extend to the mine and not the refining stage (Spuerk, et al., 2017). This also depends on the system of interest.

The success of this study relied on the availability of data, which enabled quantifying the resource intensity of water, energy and other consumables. The Global Reporting Initiative (GRI) protocol was formed by the United Nations, governments, industry and civil society with the aim of establishing standard guidelines on sustainability performance reporting within the mining and metals industry (Calvo, et al., 2016).

Numerous mining companies have begun publishing sustainability reports using the guidelines of the GRI alongside other external standards. Even though the GRI framework has been by most reporting companies, it is not a legal obligation (Spuerk, et al., 2017). These reports are usually published together with financial performance reports (Mudd, 2007a; Calvo, et al., 2016). It should be noted that voluntary instruments tend to be based on self-interest, thus changes in behaviour may be less evident than rhetoric (IIED, 2002).

The environmental information published is usually presented as inventory flows. The framework also does not have standardised guidelines of measurement, data quality and interpretation (Spuerk, et al., 2017). Furthermore, some of the reporting is characterised by discontinuous data reporting, inconsistent formatting and aggregation across geographic sites (Azapagic, 2004; Spuerk, et al., 2017). This can make comparison difficult as it distorts contest and risks losing meaning (Spuerk, et al., 2017).

Resource intensity was identified as the metric for measuring resource efficiency. Sustainability reports were would be the primary source of data. Although the GRI is the mostly widely used framework for sustainability the data, the reporting has been noted to inconsistent.

2.4 Discussion of previous similar studies

In this section, prior studies on several mining industries and their environmental impact have been reviewed. Whilst these studies were not strictly focused on resource intensity, the indicator was used to quantify recourse usage and emissions generated trends. Furthermore, the investigation methods utilised including the use of trends was reviewed. This section compares these studies for similarities, differences and learnings, which were carried over to this study. The studies reviewed are summarised in Table 2-3.

Table 2-3: Summary of similar previous studies consulted

Study	Scope	Methodology	Conclusions
(Mudd, 2007a) • Investigated resource intensity trends of gold mining amidst environmental concerns and changing ore grades	• **Gold** • Africa, Australia, North America & Asia-Pacific	• Investigated ore grade, gold production, waste volumes, greenhouse gas (GHG) emissions, energy use, water use, cyanide use, available economic resources, etc. • Data (assumed high quality) from companies, governments and other mining periodical	• Ore grade was decreasing over time • Cyanide, water, energy use and GHG emissions increased with decreasing ore grade • A resurgence in production volumes because of advancing technology (modern earth moving equipment, development of carbon-in-pulp (CIP) milling technology) • Results varied with operation conditions
(Gediga & Russ, 2007) • Ferrochrome LCA study by ICDA to update previous for benchmarking	• **Ferrochrome (FeCr)** • 7 ICDA FeCr producers • 62.1% FeCr global production • Years 2003 to 2005 • Finland, Kazakhstan and South Africa	• LCA approach • Data collection from participating companies (material flows and energy consumption) • Horizontal averages were taken for each unit process type • A distinction was made between process unit averages • Furnace technology was differentiated	• The industry was more energy efficient in comparison to the 1999 study • Closed furnaces with preheating were found to be most energy efficient, followed by closed furnaces without preheating and open arc furnaces • The industry was predicted to be more energy efficient with more closed furnaces being used in the industry • The same trend was observed with CO_2 emissions

Study	Scope	Methodology	Conclusions
(Glaister & Mudd, 2010) - To evaluate the environmental impacts of Platinum Group Metal (PGM)	- **PGMs** - 5-10 years prior to the publication of this study - South Africa & Zimbabwe	- Mostly used sustainability reports - Investigated sustainability indicators (GHG emissions, water discharge, energy and water use) - Predicted GHG emissions based on processed ore grade and technology used remained constant - Ore grade and technology were assumed to remain constant over time	- Ore grade was declining although the reserves were found to be consistent - GHG emissions increased per unit product over time and were predicted to increase due to increasing depth and decreasing ore grades - Water use efficiency was not influenced by scale, ore grade or time - Energy efficiency was invariable over time, whilst ore grade had a subtle correlation. Decreasing production had decreased efficiency - Underground mines produced more waste rock than open cut mines
(Northey, et al., 2013) - Assessed publicly available data from copper company financial and sustainability reports to determine environmental impacts and suitability for use in LCA studies	- **Copper** - Australia, Argentina, Canada, Chile, Finland, Laos, Papua New Guinea, Peru, Turkey, South Africa & USA - Copper companies' reports published from 1996 to 2010	- Investigated the effect of processing routes and declining ore grade on water, energy and GGE intensity - Data were sourced from company sustainability and financial reports - Reports were analysed for consistency and whether they could be used for LCA studies - Data gaps were calculated from other data	- Ore grade was declining causing an increase in energy intensity and GHG emissions, but insignificant effect on water - Grind size and smelting technology affected energy intensity Underground mining required more energy - Water intensity was higher with regions with high water scarcity - Pyrometallurgical routes produced more GHG

Study	Scope	Methodology	Conclusions
			emissions than hydrometallurgical routes - Low quality and scarcity of water led to an increase in energy required to transport and treat the water, leading to increased GHG emissions
(Calvo, et al., 2016) - Investigated energy consumption as a function of ore grade	- **Gold, silver, copper, lead, zinc & nickel** - Up to 2014 with varying lower limits - 16 multinational mining companies	- Focused on energy consumption as function of ore grade over time - Sustainability reports were main data source - Comparison based on metal and production route	- Ore grade was decreasing over time - Resource use and waste generation was noted to increase with decrease in ore grade but there was no clear conclusion regarding specific resource use and ore grade - Energy consumption per unit product metal increased over time due to decreasing ore grade (particularly with underground mining) due to ventilation and depth

The studies reviewed had varying goals, however they were all concerned with characterising and understanding one or more mineral processing industries' environmental impacts and energy requirements. Glaister and Mudd's (2010) research, which developed projections of greenhouse gas (GHG) emissions related to copper processing, was also used. The study by Northey et al. (2013) also determines whether the sustainability data reported could be used for Life Cycle Assessment (LCA) studies.

2.4.1 Methodology review

In all the studies reviewed, save for Gediga and Russ' (2007), the scope extended over more than one production year. This was because the study was focused on producing a Life Cycle Assessment (LCA) of the ferrochrome industry partly for benchmarking. It should be noted that Gediga and Russ (2007) compared their results to a previous ferrochrome LCA study commissioned by the International Chromium Development Association (ICDA).

Most of the studies relied on data collected from publicly available resources, such as company published sustainability and financial reports. The studies assumed that the reporting quality was uniformly high enough for comparison.

Despite this, Mudd (2007a) noted that the reports he studied were inconsistent – including within one company's annual reports. This means that even though mining companies were noted to be using the GRI framework for reporting, inconsistencies were still present (Northey, et al., 2013). These inconsistencies resulted in data gaps, which were overcome by mass balancing or using other data points to calculate missing data. Furthermore, some of the data reported were aggregated, which limited the analysis and therefore the knowledge that could be derived from them.

Gediga and Russ' (2007) study relied on the participation of seven ferrochrome-producing ICDA members to submit data, which were then reviewed by experts. The nature of LCAs and the collaboration of the ICDA members enabled the study to distinguish the environmental impacts at the mining, beneficiation and smelting stages of processing. Moreover, the study evaluated the environmental impacts of specific ferrochrome production technologies. Northey et al. (2013) also compared processing routes, although their study was focused on copper production.

The studies reviewed used the collected data to develop resource intensity trends (Mudd, 2007a; Glaister & Mudd, 2010; Northey, et al., 2013; Calvo, et al., 2016). Whilst resource intensity can be defined as an indicator of resources consumed (including water, energy, etc.); emissions or waste produced per unit of metal or per unit of milled ore were also included these studies.

The indicator is defined to compute weighted quantities, which is an ISO 14044 LCA standard (Northey, et al., 2013). Resource intensity in this respect can be used for a qualitative investigation, including determining the effect of technological innovations, production scales, and other contextual conditions (Calvo, et al., 2016). The results of studies such as these are essential tools for life cycle analysis and cleaner production (Mudd, 2007a).

2.4.2 Findings

Ore grade

In all the studies that investigated ore grade, it was concluded that ore grades are declining and that this decrease is likely to continue over time. Calvo et al. (2016) argued that higher grade ores are exploited first, with the anticipation that technology will advance over time, allowing lower grades to be economically exploited later. Glaister and Mudd (2010) noted that there was a decrease in ore grade in the PGMs, however PGM reserves are consistent in grade, hence it was not expected to decrease significantly.

At times high grade ores may be available, however environmental restrictions such as water and chemical scarcity, stringent pollution regulations, limited supply and capacity of energy, and socio-economic constraints can make a mining project unfeasible (Mudd, 2007a).

Resource intensities

Decreasing ore grade was observed to result in increasing resource input and waste outputs (Mudd, 2007a; Glaister & Mudd, 2010; Northey, et al., 2013; Calvo, et al., 2016). This because ore grade resulted in decrease yield. For instance, the study into the gold industry by Mudd (2007a) revealed a significant correlation between gold ore grade and specific GHG emissions, energy requirements and cyanide consumption. Whilst Calvo et al. (2016) observed an increase in resources and waste with decreasing ore grade, this trend could not be confirmed for specific (per unit product) quantities. This was attributed to the differences in production technology.

GHG emissions and energy

A correlation between ore grade, energy efficiency and GHG emissions was observed in the copper industry (Northey, et al., 2013) across all the studies reviewed (Mudd, 2007a; Glaister & Mudd, 2010; Calvo, et al., 2016). Decreasing ore grade leads to increasing energy requirements to process the ore, as well as greater depths and ventilation requirements in the case of underground mining (Glaister & Mudd, 2010; Glaister & Mudd, 2010). Increasing energy requirements result in increased GHG emissions, which suggests that the most energy sources are carbon based, such as in South Africa where electricity production is largely coal-based. A prime example is the PGM industry in South Africa (Glaister & Mudd, 2010).

Contrary to this was the LCA study conducted by Gediga and Russ (2007), which concluded that GHG emissions and energy efficiencies were increasing in the ferrochrome industry. The configuration of closed furnaces with preheating was noted to result in lower energy requirements and GHG emissions in comparison to just a closed furnace or an open furnace. Due to the favourable results, the configuration's popularity in the industry was increasing. Although the ore grade trends were not indicated in the study, it is plausible that the trends would show a constant ore grade or declining ore grade over time. Therefore, in this case, technology mitigated the increase in resource requirements and associated wastes.

In the study by of Northey et al. (2013), ore grade was determined to be decreasing, however the pyrometallurgical processes were concluded to require more energy than hydrological routes. Similarly, underground mining has been shown to require more energy and produce more waste rock than open pit mining (Calvo, et al., 2016). The introduction of the carbon-in-pulp (CIP) process and the advancement of earth moving equipment in gold production led to a resurgence in gold production (Mudd, 2007a), while grind size had a significant effect on energy intensity as the ore grade decreased (Northey, et al., 2013). Technology and the choice of processing route can therefore significantly offset resource use and waste production, despite declining ore grade, to the extent of increasing production volumes.

Water

Regarding water intensity, Mudd (2007a) concluded that water intensity increases with decreasing ore grade in gold production. On the other hand, ore grade was concluded to have an limited effect on water intensity in the copper industry (Northey, et al., 2013). Differences in the production technology used was part of reason for the limited effect of ore grade. Furthermore, regions in arid climates was found to require more water due to evaporation water losses. However, strategies can be put in place to reduce water intensity through filtering tailings and evaporation prevention (Northey, et al., 2013).

Glaister and Mudd (2010) also found that ore grade had limited effect water intensity in PGMs. The level of efficiency seemed to be site specific. In addition, the aggregation of data limited the analysis. In metal industries other than gold, the ore grade does therefore have a significant impact on the water intensity.

Northey et al. (2013) further noted that a low quality of water and high levels of water scarcity lead to increased energy requirements to treat the water and transport the water to the processing site. Increased energy requirements in turn lead to increased GHG emissions due to energy sources being primarily carbon-based.

2.4.3 Synthesis

It is evident that ore grade has appreaciable effects on the intensity of mineral resources.Calvo et al. (2016) stated that declining ore grade should not be viewed to signify depletion or declining availability because of other influencing factors such as future innovations which may not be factored in. A good example of this is the resurgence of gold production due to the CIP process and the advancement of earth moving vehicles, as noted by Mudd (2007a). It can therefore be inferred that, if technology can affect can influence yield and resource intensity.

Throughout the studies reviewed, the variability of reporting styles, technology routes, site conditions and aggregation of results led to several inconclusive results regarding certain resource intensities. Gediga and Russ (2007) mitigated this challenge by including experts who could corroborate the results of their study.

The studies reviewed focused on the environmental impacts of producing various mineral. Data for the studies were mostly obtained from company sustainability and financial reports, however as these data were inconsistently reported, where possible other data points were used to address gaps. The data were assumed to be uniformly of a high quality for comparison.

Resource intensity was used as a weighted indicator, which enabled a comparison to evaluate the effect of various operating conditions. In addition to resources, including waste and emissions intensities were also evaluated literature. Ore grade trends were evaluated to ascertain the effect of resource intensity trends on the various mineral industries. Ore grade was observed to be decreasing for various mineral industries, which led to increasing various resource intensities. Resource intensities were observed to be influenced by the mineral industry, regional water scarcity and quality conditions, technological innovations and processing routes, however factors such as site-specific operating conditions and reporting styles hampered some of the studies. This challenge of data quality was mitigated by having experts corroborate the results.

2.5 Chapter summary

The literature review has shown that resource efficiency in a mine-to-metal value chain can be achieved by assessing and monitoring the industry through sustainability indicators. Improving resource efficiency in manufacturing is associated with reducing negative environmental impacts whilst improving the resilience of the operation through reduced costs.

Resource intensity, which is also a normalised indicator, was chosen for this study as it is defined as measuring resource efficiency. Studies that had used resource intensity were reviewed and it was noted that most relied on publicly reported company data.

Trends were used to determine changes in resource intensities. The compiled trends compared ore grade trends, environmental impacts, resources used in different operations, and varying operating conditions such as scale, technology and processing routes applied. Expert opinions were used to corroborate the results. At times the reporting was not consistent within a company over consecutive years, therefore mass balancing techniques were used where possible to calculate missing data points from available data points.

In all the studies reviewed, the ore grade was found to have decreased over time due to the most accessible higher grades being exploited first. The decrease in processed ore grade resulted in an increase in resource intensity. This includes specific material inputs such as cyanide in gold production, and energy consumption with respect to most mineral resources. In regions where the national electricity supply grid was carbon based, it was determined that increase energy consumption would result increasing greenhouse gas emissions.

In some instances, new technology mitigated the effects of decreasing ore grades, such as advancing earth moving equipment and carbon-in-pulp technology in gold production, and closed furnaces in ferrochrome production. Differing operating conditions have also influenced resource intensity trends.

3. METHODOLOGY

There is a need for a systematic analysis of the South African ferrochrome industry, given that the goal of the South African government is to develop the chromium value chain because of the abundant raw material present in the country. Chapter 2 investigated the decoupling of production output from environmental impacts, as ore grade is noted to have a significant effect on resource intensities. This chapter presents the hypothesis and research questions, followed by a description and reasoning for the approach and methods selected for this study.

3.1 Hypothesis

Based on the preceding chapter, it is hypothesised that the resource intensities in the South African ferrochrome industry have increased over time, due to declining yields of ferrochrome per ton ore mined over time. This increase, however, may have been offset by the implementation of innovations in the industry.

3.2 Research questions

The following research questions were asked in order to test the hypothesis:

- How has the mass yield for South African ferrochrome production changed over time?
- How have the resource intensities of ferrochrome production in South African changed?
- What has been the impact of technological changes on the resource intensity trends?
- What are the drivers for the resource intensity changes?

3.3 Research approach

To answer the research questions, this dissertation combined a quantitative data mining approach to compile resource intensity trends (section 3.3.1) with qualitative methods, whereby major events in the industry (major projects to change the industrial infrastructure) were mapped and industry experts were identified and consulted to corroborate the trends and to establish the impact of technology and its drivers on the South African ferrochrome industry (section 3.3.2). The quantitative data were compiled from secondary data through a desktop study, while the qualitative data were compiled from primary and secondary data sources through a desktop study and interviews. An analysis of the data collected is discussed in section 3.3.4.

3.3.1 Data collection

To ascertain if there had been changes in ore grade over time, it was essential to first collect ore grade data spanning multiple years. As the focus of this study was the South African ferrochrome industry, the sector was first investigated via a desktop study to determine the state of the industry, particularly the major ferrochrome production companies, between 2007 and 2017.

Once the companies were identified, data were collected from their published sustainability reports and related industry publications. It was assumed that all data collected were of a similarly high quality and could therefore be compared, pending the commentary of the interviewees.

Data pertaining to resource intensity were also collected in the same manner as that for ore grades. These data included water consumption, energy consumption and electricity consumption, in addition to ore grade data. It should be noted that one of the interviewees supported this study by availing sustainability data which were not published at the time. Once collected, the data were used to calculate resource intensity, i.e. the resources consumed per unit of product, for multiple years (Mudd, 2007a). The equation used to calculate resource intensity for this study was Equation IV.

Equation IV

$$Resource\ intensity_i = \frac{Quanity\ of\ resource\ consumed_i}{Mass\ of\ ferrochrome\ produced_i}$$

The letter ***i*** in the equation represents the production year, while quantity of resource may refer to volume of water or power units for electricity. The dimensions were thus dependent on the resource. Ferrochrome mass units were kilograms, such that the resource intensity unit results would be per unit kilogram of ferrochrome produced. It was noted in section 2.2 that the composition of ferrochrome products varies, however in this study it was assumed that the product mix was consistent such that product differentiation would not significantly affect the results.

Gediga and Russ (2007) completed an LCI study which was based on 1 kg of chromium as opposed to 1 kg of ferrochrome, because of the variability of ferrochrome mass. Nevertheless, that study had the support of the ICDA and its members, who contributed the necessary data to complete the study. As this investigation relied on published data, it could not complete the same calculations.

It was noted by Mudd (2007a) that company sustainability reports can publish results differently, or at times do not publish certain results from year to year, thereby creating data gaps. Azapagic (2004) pointed out that this could be overcome by mass balance modelling when there is enough data to do so. Where possible, any gaps were thus overcome by calculations from other data points using mass balance techniques.

The effects of changes in production processes and technological innovations on resource intensity trends were assessed through an event history analysis (EHA) approach. EHA can be defined as a research method for determining occurrences of interest within a history of events. Events refer to changes in operation in this study. This can be useful in determining the cases of those events (Steele, 2005). In this study, changes in processing were identified and catalogued through a desktop study, with the aim of determining the effects of those changes on resource intensity trends. Sustainability reports, media publications, ferrochrome company websites and environmental impact assessment (EIA) reports, in addition to expert consultations, were consulted.

In some publications, resource intensity data were reported with cause of variations, particularly in the company sustainability reports.

3.3.2 System boundaries

The system boundaries of the study was set to include chromite mining activities, concentration and smelting to produce ferrochrome. A preliminary overview of the data available showed that the ferrochrome production companies also sold some of the concentrated chromium ore that they produced. This presents some allocation and attribution challenges. Material entering the ferrochrome value chain from the PGM sector was accounted for burden-free of any mining and concentration activities necessary for PGM production. The published data was also limited in that product allocation could be accomplished. Furthermore, that data obtained did not cover the same system boundaries. This makes the results more challenging to compare between companies. Be that as it may, there was some consistency in some of the reporting of individual companies which enables the effect of events and technological processing to be identified. In addition, differences in reporting scope were discussed.

3.3.3 Interviews with industry experts

As mentioned in the previous section, determining whether technological changes influenced the trends was partly investigated through the interviews. Thematic analysis was used to analyse the data retrieved from the interviews. Interviewees were identified in part through the desktop study, which was undertaken to determine projects aimed at resource intensity. EIAs and other publications that cited experts involved in the implementation of the technology were also used. Finally, the initial interviews were instrumental in identifying other interviewees through referrals.

Different types of experts were sought based on their experience of operations and knowledge of ferrochrome production, in particular their knowledge with respect to production environmental exchanges. This included sustainability production officers, engineering design technologists and environmental consultants.

Interview requests were sent via email with a brief description of the study and an outline of what the contribution of the interviewees would be. Furthermore, the terms of the study pertaining to the use of the interview results and other ethical concerns were set out. In addition, the preliminary results of the study, as per Appendix B.3, were presented in the interview request email.

The interviews were semi-structured, as while they were guided for specific data gathering, it is also possible to enquire about other aspects that arose in the course of the interview. The interviews were recorded using a sound recording function on a cell phone, while notes were also taken. Thereafter the interviews were transcribed, after which the results were coded into themes. One interview was conducted telephonically and as a result could not be recorded, however notes were taken to capture the outcome of the interview.

The interviews were designed to commence with the interviewees and interviewer getting acquainted. Thereafter a brief overview of the report was presented to the interviewees. At this point the interviewees were requested to sign the consent form (discussed in section 3.4) which outlined the terms of the interview. Subsequently, the interviewees described their professional skills and experience in relation to the ferrochrome industry.

The interviews then proceeded with the interviewees commenting on the accuracy of the preliminary results and sharing their insights into changes in ferrochrome production that may have led to the state of the preliminary results, as well as similar changes or related projects that they have worked on and projects that their organisation undertook to improve resource intensity. In discussing the impact of technological changes, the participants also explained the reason for some of the projects or operational changes. The interviews lasted between 60 and 90 minutes.

3.3.4 Interviewees conducted

Select stakeholders with technical insight into the ferrochrome industry were interviewed (see able 3-1). The participants were assigned pseudonym codes based on the type of organisation and the position they held. This discreet coding system was adopted to protect the identities of the participants.

able 3-1: Particulars of interviewed participants

Participant(s)	Type of organisation	Position
FP1-EM & FP1-WM	Ferrochrome Producer 1	Group Environmental Manager & General Works Manager
FP2-SS	Ferrochrome Producer 2	Safety and Sustainable Development Head
FP2-WM	Ferrochrome Producer 2	Production Manager
CF1-Dir	Consulting Firm 1	Director
CF2-Dir	Consulting Firm 2	Director

3.3.5 Participant overview

The participants' backgrounds, including academic qualifications, field experience and organisation type and role, are all discussed to show the suitability of the participants for the interviews.

FP1-EM and FP1-WM

FP1-EM and FP1-WM were in senior management in one of the largest (in terms of production volume) ferrochrome producers in South Africa. FP1-WM had over 25 years' experience in the industry, holding several technical positions such as engineering manager, production manager and works manager. At the time of the interview, FP1-WM led a team at a ferrochrome processing plant. The lengthy technical experience and expertise held by this participant were regarded sufficient for the participant to know about the technology and trends of the industry.

FP1-EM had experience in technical ferrochrome production with specialised knowledge in energy and environmental management, and was leading the environmental team of the organisation at the time of the interview. In addition, this expert managed a large aspect of the organisation's resource intensity with the support of the team, whilst fulfilling duties pertaining to the organisation's environmental regulatory compliance. Naturally, their experience in resource intensity management and technical knowledge made this participant valuable to the study.

These participants, who were interviewed concurrently, shared in-depth insights into the variations of the resource intensity trends with respect to the industry and their organisation. Furthermore, some of the industry developments affecting the trends were ascertained.

FP2-SS

Participant FP2-SS was an environmental officer in a large ferrochrome producer in South Africa, with in excess of ten years executing roles related to sustainable development. This encompassed matters of environmental management, including associated assessment reporting and compliance to best practice. Furthermore, this participant had a postgraduate academic qualification, having completed research regarding industry waste management prospects. The participant was knowledgeable about some of the innovations around production and environmental technology that have occurred in their organisation and the industry. Having recently completed their postgraduate qualification; the participant was sympathetic to the study and gave detailed explanations to the questions asked.

FP2-WM

FP2-WM was a works manager at one of the largest ferrochrome production companies in South Africa, having worked in other large South African ferrometal companies. This participant had several years' experience overseeing different aspects of ferrochrome production, ranging from beneficiation to pelletising, sintering and smelting. In addition, FP2-WM had experience in Safety, Health, Environment and Quality (SHEQ) management in the ferrochrome industry. Furthermore, the participant had recently completed research in the industry.

This broad and lengthy experience in the industry enabled the participant to share useful insights into the technical aspects of production and the changes therein. Due to limited resources and the interviewee's distance from the researcher, this interview was conducted telephonically. FP2-WM was able to answer questions regarding some technical aspects of the industry in detail, regardless of the nature of the interview.

CF1-Dir

CF1-Dir was part of senior management at an energy consultancy firm, who had previously worked for other similar companies within energy optimisation. They had also worked with numerous ferrochrome production companies in South Africa on research and development and construction, and on implementing projects regarding electricity cogeneration, energy optimisation and carbon footprint mitigation. In addition, the participant had worked in advisory roles with independent power producers (IPPs).

The participant's experience in energy and emissions reduction was crucial to understanding the drivers and development of the industry, particularly in energy innovations. This participant was able to give insight into several dynamics and drivers surrounding energy and emissions reductions and the outlook of the industry.

CF2-Dir

CF2-Dir was a professional environmental scientist with expertise in chemical toxicology and waste classification amongst other skills. CF2-Dir was also an academic with experience in South Africa and internationally, which included waste assessment and classification for the ferrochrome industry. This participant had been appointed as an advisor to several industry bodies, one of which belongs to the South African ferrochrome industry. This participant thus had unique knowledge about the industry with regards to waste and environmental management, which was useful to this study.

It is worth mentioning that other experts were contacted regarding this study, however due to unfavourable logistics concerning resources and privacy policy barriers, their participation could not be secured. Regardless, the compiled interviews were considered adequate for the purposes of this study.

3.3.6 Data analysis

Having compiled the resource intensity trends and the sustainability projects, the interviews were analysed using thematic analysis as described by Braun and Clarke (2006). This entailed transcribing the interviews verbatim. Following this, relevant information was coded by extracting key points from each participant. These points were organised according to the themes that emerged. After the initial grouping, the emerging themes were assessed to prevent repetition and to refine the themes in order to be coherent. Thereafter, the themes were reviewed to ascertain whether they represented the views of the interviewees. These results were then compared to the resource intensity trends and sustainability projects.

3.4 Ethics

The interviews were conducted in accordance with the university's (UCT) guidelines, which required the approval of the Engineering and Built Environment's Ethics in Research Committee (EiRC). The interviewees participated voluntarily in the study, as per the consent form (appendix B.2). The forms also indicated that the interviews would only be used for academic purposes.

Although no potential harm to participants was foreseen, it was thought best to keep the identity of the participants anonymous to guard against any unintended consequences. In order to ascertain the credibility of the experts, however, it was decided to disclose their occupations.

4. RESULTS AND DISCUSSION

The results of this study have been compiled in this section. Resource intensity trends from the data mining and commentary from expert interviews will be discussed, followed by a review of projects relating to resource intensity trends in the industry and factors influencing the projects. Finally, the synthesis of the results is discussed in relation to the research questions.

Ferrochrome producers are largely situated in the Bushveld Igneous Complex and have a chromite mine within their business assets (Pan, 2013). To establish adequate representation of the industry, the number of producers and their production capacity were determined. Table 4-1 shows South African ferrochrome production companies' capacities and production status.

Table 4-1: Overview of the ferrochrome producers in South Africa (Moorcroft, 2016; Pastour, 2018)

Company	Capacity (kt/y)	State 2014/5	State 2018	Integrated mines
Glencore Merafe (Xstrata)	2000	Active	Active	Yes
Samancor Chrome Limited (Samancor)	1200	Active	Active	Yes
Tata KZN (Alton North)	150	Active until June 2016	Furnaces offline (Went into business rescue)	Yes
Afarak Includes Mogale alloys processing plant	110	Active	Active	Yes
Hernic Ferrochrome	420	Active	Active (business rescue investigation)	Yes
International Ferro Metals (IFML)	267	Active	Business rescue (acquired by Samancor)	Yes
ASA Metals (Newco)	410	Active	After business rescue it was acquired by Sinosteel Corporation Limited and Samancor to	Yes

Company	Capacity (kt/y)	State 2014/5	State 2018	Integrated mines
			form the Newco a joint venture[1]	
Assmang Chrome	Unknown	Three out of four smelters were converted for ferro manganese production from 2010. The remaining ferrochrome smelter has been idle since 2012 due to the unfavourable ferrochrome market.		Yes

"Business rescue is a South African statutory means of enabling a financially distressed company to continue operating whilst under the supervision of a business rescue practitioner (BRP) protected from its creditors" (IFML, 2015, p. 3).

It can be observed that three of the eight producers were active between 2014/5 and 2018, whilst the other five producers had applied for business rescue and/or had stopped producing ferrochrome. It should be noted that whilst businesses are under business rescue, they may still be active. Furthermore, certain companies produce more than one alloy product, such as Arafak which produces silico manganese, ferrochrome and stainless steel.

Glencore-Merafe, the leading producer in terms of production volume, publishes its sustainability performance results regularly. IFML also publishes reports, but not all of them could be obtained for all production years. These results were presented in accordance with the Global Reporting Initiative (GRI) framework. Another South African ferrochrome producer that does not publish its sustainability results supported this study by presenting its results for this study. This company shall be referred to as B2 so as not to disclose the identity of the company.

4.1 Resource intensity trends

The resource intensity trends of the South African ferrochrome industry are presented in this section. The resources considered were chromite, water, energy (specifically electricity) and reductant. However, to calculate resource intensity trends, an annual production trend was also compiled.

4.1.1 Production

South African ferrochrome production trends were compiled from 2006 to 2017 for the different companies, as shown in Figure 4-1. Production details were not readily available for all companies, thus production capacities were used for approximation when data were not available. In addition, companies such as TATA KZN and

Assmang Chrome were not producing ferrochrome throughout the period under review.

It is, however, highly unlikely that all these companies operated at constant full capacity over the period. Furthermore, some companies' furnaces, such as Tata KZN, have been reported to be offline (Moorcroft, 2016), therefore the trends for the other companies are not accurate.

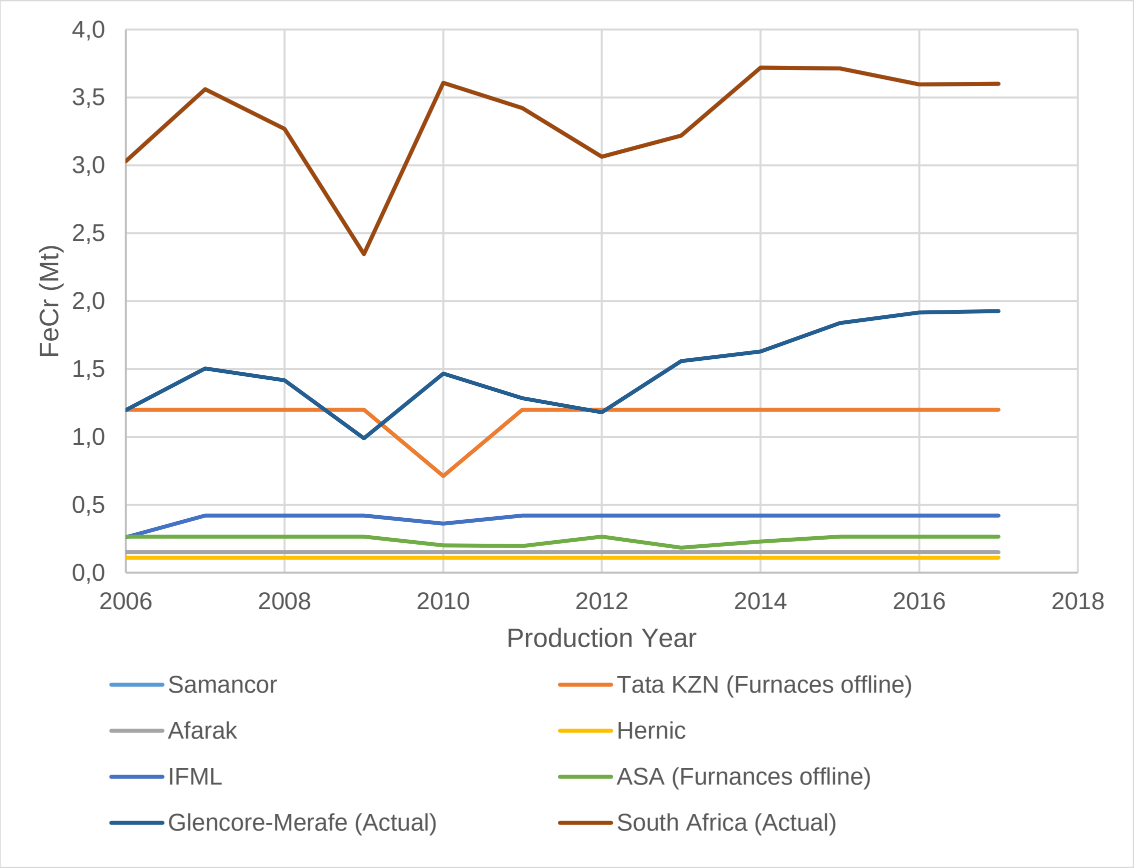

Figure 4-1: South African companies' ferrochrome production trends (Xstata-Merafe, 2009; 2011; IFML, 2011; 2014; Glencore-Merafe, 2014; 2015; 2017)

According to Figure 4-1, ferrochrome production in South Africa has fluctuated over the years, with a significant decrease in production in 2009. Overall production increased by 18.9% between 2006 and 2017, however. From 2012, Glencore-Merafe's (formerly Xstrata) production can been seen to have increased up to 2017, while IFML's production fluctuated but had no discernible net change over the period. As was previously noted, Glencore-Merafe and IFML were the only South African FeCr producers that publicly reported on performance, thus capacities were used to estimate production for the other companies.

4.1.2 Ore

Production volumes are directly affected by the quality and quantity of ore used. The ore grade trend could not be determined due to insufficient data, however an ore intensity trend was compiled as per Figure 4-2.

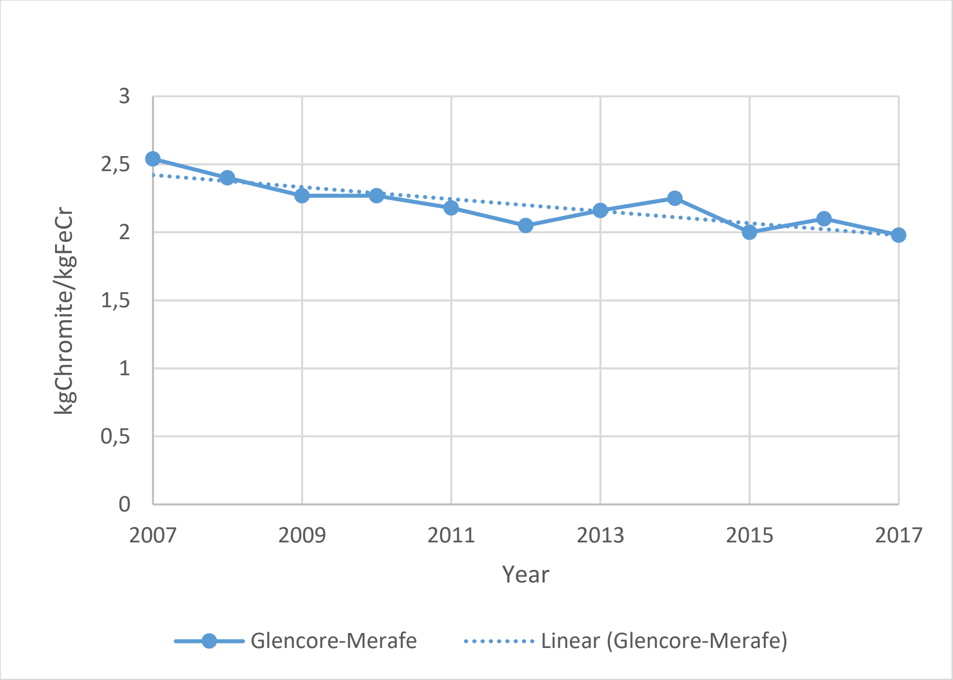

Figure 4-2: Chromite intensity Glencore-Merafe only (Glencore-Merafe, 2012; Glencore-Merafe, 2015; Glencore-Merafe, 2017)

Figure 4-2 shows that chromite intensity declined by 20% over the period, whilst production increased. In 2014, the Lion II project was commissioned which resulted in an increase of chromite intensity. The commissioning and starting up of these furnaces were described as requiring a higher than average operational ore input (Glencore-Merafe, 2014). IFML (2014, p. 8) also reported inefficiencies due to strike action in the platinum industry. Chromite also includes pellets sourced from chromium concentrate from UG2 platinum group metals (PGM) tailings.

Figure 4-3 shows the yearly production of UG2 based chromium concentrate.

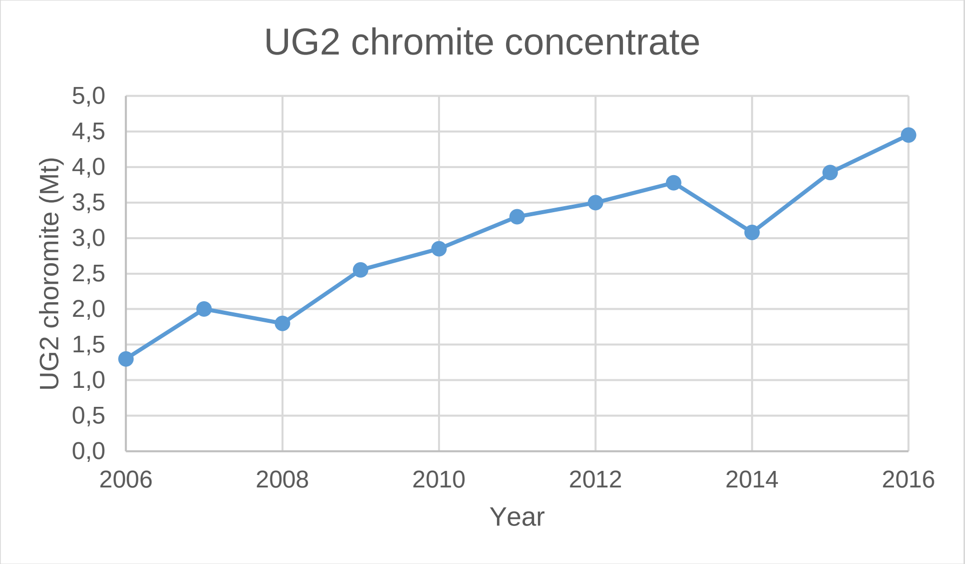

Figure 4-3: Chromite derived from PGM (UG2) operations' annual production (ICDA, 2016)

Based on Figure 4-3, UG2 chromium concentrate production increased by an average of 15% a year between 2006 and 2016. UG2 chromium concentrate is sourced from the PGM industry and pelletised and sintered before being consumed by the ferrochrome industry. Production increased every year within the period studied, with the exception of 2014 (Glencore-Merafe, 2014, p. 5). This decrease was due to a five-month long strike in the South African platinum industry. Despite the 2014 decrease, the concentrate increased, which is consistent with a forecast by Cramer et al. (2004), who stated that there would be an increase of UG2 concentrate intensity by the ferrochrome industry, with resultant increased production by the PGM industry. This is discussed further in section 4.2.1.2. Directly related to ore intensity trends are mineral waste production trends, which are shown in Figure 4-4.

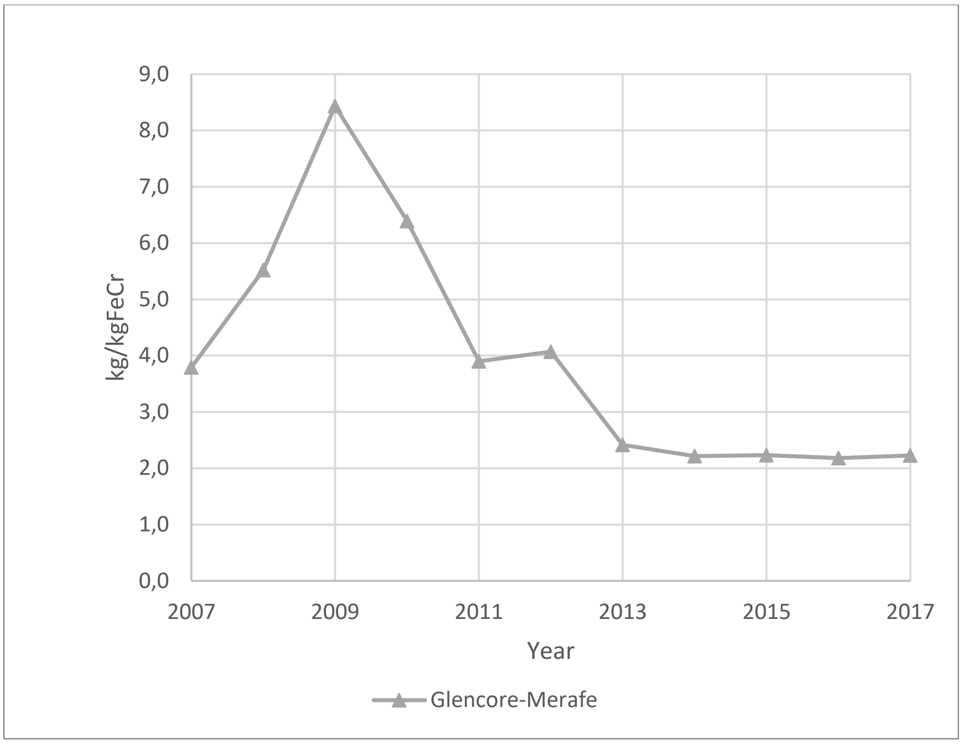

Figure 4-4: Mineral waste produced annually Glencore-Merafe only (Glencore-Merafe, 2012; 2015; 2017)

Mineral waste, as reported in Figure 4-4, includes ferrochrome processing waste such as slag, and mining waste such as run-off and tailings. It can be observed that mineral waste intensity peaked in 2010, which has been attributed to the commissioning of the Lion Project and the resumption of several furnaces, which had been offline because of the financial recession of 2008/9.

Although after 2013, waste intensity decreased and yet ferrochrome production increased. This was the effect of more efficient processing. When comparing the ore intensity and the mineral waste production, it can be noted that that the mineral waste is greater than ore intensity. This was an effect of some of the chromite ore mined and concentrated by the company being sold off and consequently not contributing to the company’s ferrochrome production.

4.1.3 Water

Water intensity trends were also compiled, with the results being set out in Figure 4-5.

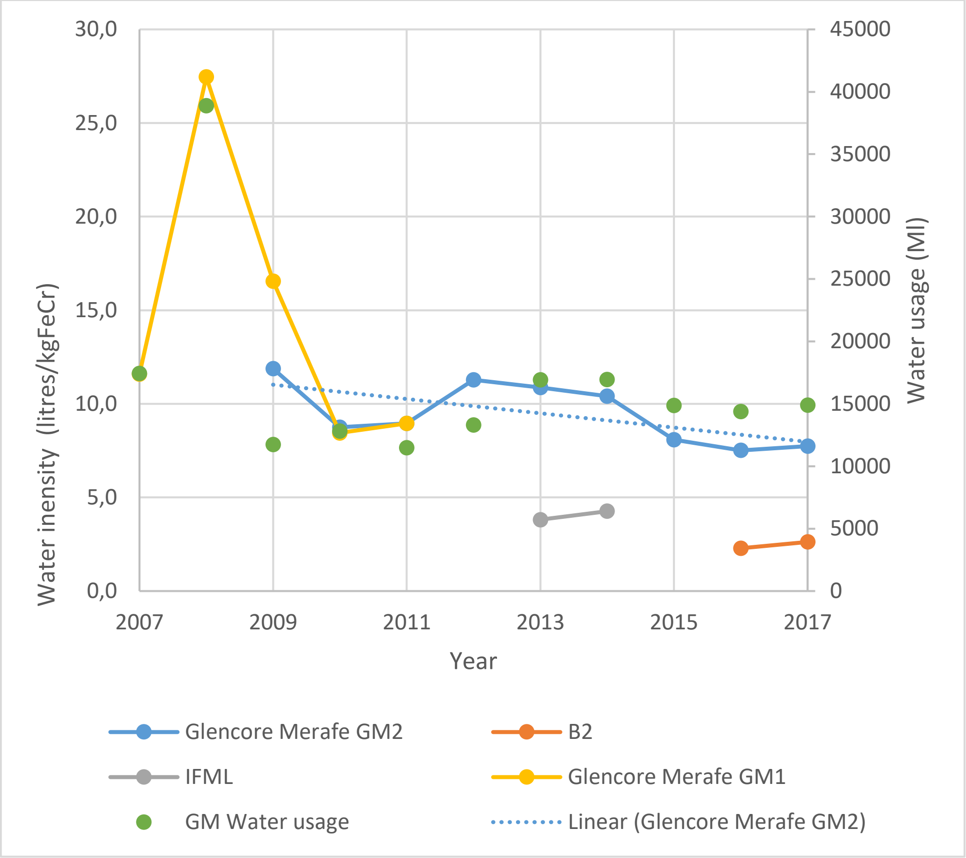

Figure 4-5: Water use and intensity for ferrochrome production for selected South African companies (Xstata-Merafe, 2011; Glencore-Merafe, 2012; 2015; 2017)

Although only two years' worth of results regarding IFML's and B2's water intensity were available, Glencore-Merafe's water intensity was significantly greater – up to twice the volume in certain instances. B2's water intensity was smaller due to the scope of water reporting being limited to processing activities after mining such as pelletising, sintering and smelting, while Glencore-Merafe included mining activities. The scope of IFML's water reporting could not be confirmed, but it was assumed that it also excluded mining activities. Although the results from B2 and IFML had a smaller difference between them in comparison to Glencore-Merafe, two years' worth of results was considered too short for a meaningful assessment of trends.

Be that as it may, water intensities were calculated from an ICDA study reported by Gediga and Russ (2007) for an average closed furnace, with preheating and mining and beneficiation included. It should be noted that the ICDA study was not limited to South Africa. The water intensity was calculated to be 13.0 litres/kg$_{FeCr}$, which was similar to the 2009 resource intensity result by Glencore-Merafe. This value included mining and ferrochrome production activities; if mining and beneficiation are excluded, the ICDA value becomes 4.62 litres/kg$_{FeCr}$, which was greater than the reported values of B2 and IFML.

In 2008 Glencore had a spike in water usage and water intensity. Although no reason was given for the spike, it was noted that site water monitoring systems were improved. About 70% of the water usage was stated to be sourced from recycling and there was the increase 131% increase from raw ground water usage. The decline in 2009 was attributed to the economic 2008 recession which resulted in a 30% reduction in production and lower 58% decrease in water usage. This translated into 39.7% decrease in water intensity.

2010, Glencore-Merafe's water intensity decreased due to an increase in water production. Water efficiency projects have also been cited as contributing to the decrease in intensity (Xstata-Merafe, 2009). Notwithstanding the projects, the same year it was reported that refinements were made to the water accounting method. This was in relation to the allocation of dirty water used for dust suppression being assigned under recycled water. The extent and the effects of these amendments could not be ascertained based on the text (Glencore-Merafe, 2012). GM1 were the initial results whilst GM2 were the result after the change in water accounting. However, if the accounting method remained consistent up to 2017, it can be concluded that water intensity decreased by 31.0% between 2012 and 2017. Even with the changes, the impact of furnaces starting is evident.

4.1.4 Energy

Energy intensity trends have been compiled and are shown in Figure 4-6.

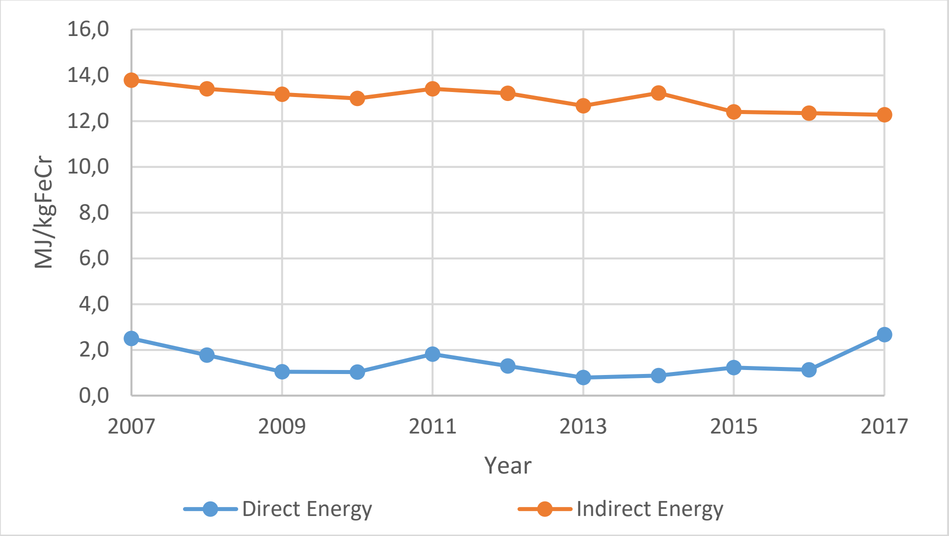

Figure 4-6: Energy intensity trends of Glencore-Merafe ferrochrome production (Glencore-Merafe, 2012; 2015; 2017)

The trends depicted in Figure 4-6 refer to Glencore-Merafe; indirect energy refers to electrical energy from the national grid; and direct energy refers to energy from fossil fuels consumed on site. Indirect energy intensities were significantly greater than direct energy intensities, while direct energy intensity was observed to fluctuate with no discernible net increase or decrease over the period. Indirect energy intensity, on the other hand, decreased from 13.75 to 12.3 MJ/kg$_{FeCr}$, despite fluctuations.

Electrical intensity trends for the given South African ferrochrome production companies are shown in Figure 4-7.

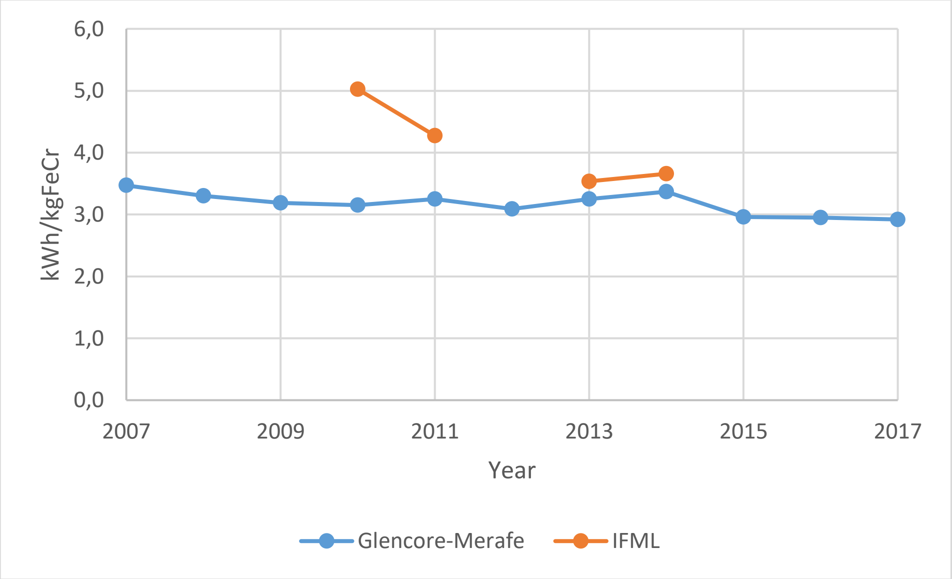

Figure 4-7: Electricity intensity trends for ferrochrome produced for the different South African companies ((IFML, 2011; 2014; Glencore-Merafe, 2011; 2012; 2014; 2017)

Figure 4-7 reveals that Glencore-Merafe's electricity intensity decreased by 14.5% between 2007 and 2017. This has been attributed to energy efficiency projects, which are discussed further in section 4.3.1. The electricity intensity decreased to the 3.0 kWh/kg$_{FeCr}$ mark in 2015. An increase in 2014 can be been credited to the commissioning of the Lion II Project, as well as the irregular supply of chromite due to strike action in the PGM industry at the time (Glencore-Merafe, 2014). This meant that the UG2 concentrate was not readily available and ultimately increased intensities. The starting up of furnaces has been noted to result in higher energy intensities and the non-ideal supply of furnace feedstock resulting from non-ideal ore mixture also results in inefficiencies

IFML (2011) can be seen to have a greater electricity intensity than Glencore-Merafe for the period, despite reporting a decrease in electricity intensity between 2010 and 2011 due to the implementation of cogeneration, which is discussed in further detail in section 4.3.1. When consulting the literature, there was no indication that Glencore-Merafe had cogeneration operations. It was reported, however, that the IFML cogeneration plant was operating non-optimally due to leaks in furnace roofs (IFML, 2011). Consequently, in 2013 and 2014 after the matter had been attended to, the electricity intensity was below 4 kWh/kgFeCr in comparison to the higher intensity in 2010 and 2011. In 2014 a slight increase (0.12 kWh/kg$_{FeCr}$) in electricity intensity can be observed. This was attributed to an increase in production. Moreover, in 2014, a new furnace was commissioned (IFML, 2014).

Both companies (except for IFML in 2010) fall within the range of the average electrical intensities (3.08 – 4.85 kWh/kg$_{FeCr}$) reported by the ICDA's (Gediga & Russ, 2007) study, as shown in Appendix A.1. Electrical intensity for ferrochrome production was estimated to be 3.3 - 3.8 kWh/kg$_{FeCr}$ by Pan (2013), and this range was closely approximated by Glencore-Merafe and IFML in 2013 and 2014. IFML's intensity for 2010 – 2011 significantly falls outside this range, which could have been the result of the cited furnace roof leaks.

4.1.5 Reductants

Although reductants are an essential raw material in the production of ferrochrome, their intensity is not explicitly reported by the companies, hence their intensity could not be calculated. Within the ferrochrome industry, there has been a growing preference for closed furnaces because of the advantages relating to emissions mitigation. The disadvantage of these furnaces is that they require more coke (from 0.31 to 0.33 kg$_{reductant}$/kg$_{FeCr}$) (Basson, et al., 2007). Moreover, coke is expensive in relation to other reductants such as anthracite. This has led to companies attempting to minimise the consumption of coke in preference to cheaper anthracite (IFML, 2014). The extent of coke intensity changes over the industry could not be confirmed as the trends could not compiled.

4.1.6 Overall trends

Production was observed to have increased, despite fluctuations. Although total South African production could be determined, individual company production trends could not be accurately determined for all companies. Ore intensity was observed to have decreased owing to increased UG2 concentrate production by the PGM industry, which indicated that intensity by the ferrochrome industry was increasing.

Mineral waste was found to have increased and plateaued for Glencore-Merafe, the main reason cited was the starting of furnaces. This was also partly due to some of the ore being sold into the market.

Although no definitive conclusion could be made regarding water intensity changes due to an amendment in water accounting methods in 2012, water intensity was observed to have decreased. This decrease is only valid if the water accounting methods remained consistent after 2012, however. the 2010 water intensity before and after the alteration is the same.

Energy intensity trends were reported for Glencore-Merafe as being indirect and direct. Even though there were fluctuations in both types of energy intensities, indirect energy intensity was greater but gradually decreased, whilst direct energy did not change significantly. With respect to electricity intensity trends, IFML was observed to have greater intensities than Glencore-Merafe. Nevertheless, both companies' electrical intensities decreased over the period.

4.2 Interview results

Expert interviews were conducted for this study to understand the extent to which resource intensity trends in the South African ferrochrome industry were influenced by changes in technology employed and deviations in processing routes. The interview responses were analysed and summarised as discussed in section 3.3.6.

4.2.1 Commentary on trends

The commentary by the participants on resource intensity trends is discussed in this section. The transcripts of the interviews can be found in Appendix B.6.

The participants were initially asked to comment on the preliminary results as shown in Appendix B.3, all the participants concurred that the results reflected the South African ferrochrome industry. Participants also stated where there were discrepancies.

4.2.1.1 Ferrochrome production

CF1-Dir (Personal communication 2018, September 7) noted that preliminary production trend results reflect those of the industry. Furthermore, the industry experiences three to five-year production cycles which are influenced largely by market factors. During these cycles, producers increase output with the increasing price of ferrochrome. In addition, producers usually increase production capacity to increase production. Conversely, production declines when the price of ferrochrome decreases. In some instances, producers opt to shut down some operations to minimise production.

4.2.1.2 Ore *intensity*

South African ferrochrome production was noted to have increased, whilst the chromite intensity was noted to be decreasing. This observation was confirmed by FP1-EM and FP1-WM (Personal communication 2018, July 3) to be the trend with other producers. FP2-WM (personal communication, August 23) also confirmed the chromite intensity decline, and stated that the range, as seen in the preliminary results, were indicative of the South African industry. However, it was noted that FP2's chromite intensity was greater than the results reported in for Glencore-Merafe.

Lumpy ore and agglomeration

FP1-EM and FP1-WM (Personal communication 2018, July 3) attributed the observed decline in intensity due to the advent of the Premus technology smelter (Lion Project) with regards to Glencore-Merafe. With reference to the industry, the decline was stated to be because of the introduction and ubiquitous application of the Outokumpu pelletising technology.

Lumpy (25 to 150 mm) ore is preferred in smelting, yet South African chromite is characterised as being brittle and mostly fine (6 mm and less). This is because ore fines decrease the permeability of carbon monoxide produced during the reduction reaction, leading to pressure building up resulting in explosions and less efficient smelting. The fines ore is normally agglomerated through briquetting or pelletising to overcome the shortage of lumpy ore (Mc Dougall, 2013). FP2-SS (personal communication 2018, July 16) also mentioned that pelletising and sintering of chromite was introduced into the industry in response to the scarcity of lumpy chromite ore for smelting.

Profitability

Furthermore, due to the prolonged exploitation of LG6 and MG1/2 seams for chromite spanning over three decades, some mines have become relatively deep in comparison to when the seams were initially mined. In addition, it was discovered that the platinum group metals (PGM) produced tailings during UG2 beneficiation, which had a significant chromium content. These tailings can be feasibly beneficiated to produce chrome concentrate with a chromium content of about 40% Cr_2O_3. This was similar to the chromium concentration from LG6 and MG1/2 chromite (Cramer, et al., 2004).

However, since the concentrate produced was fine as opposed to lumpy, it was necessary to agglomerate it through pelletising and sintering so that it could used as chromite for ferrochrome production. UG2 concentrate can only be used in for ferrochrome production as sintered pellets (Basson & Daavittila, 2013).

LG6 and MG1/2 seams are considered to be the best and most financially viable because of their high Cr:Fe (chromium to iron) ratio (1.5-2 after beneficiation), as opposed to the low UG2 ratio (less than 1.4 after beneficiation). A high Cr:Fe ratio is regarded as the most indicative measure of ore grade because it is one of the factors that determine the chromium content in the ferrochrome product; a higher content of chromium can be expected with greater ratios (Cramer, et al., 2004). Furthermore, it was noted that iron reduces more readily than chromium, therefore virtually all the iron from the ore is present in the product. Thus, the greater the Cr:Fe ratio, the greater the chromium content in the ferrochrome product (Neizel, et al., 2010).

Nevertheless, ferrochrome producers have increased pelletising and sintering capacity to source chromite from the PGM industry. This is because the cost of buying UG2 chrome concentrate, pelletising and sintering, combined with the lost revenue from reduced chromium content with regards to Cr:Fe ratios, is cheaper than the cost of mining and beneficiating LG6 and MG1/2 (Cramer, et al., 2004). FP1-EM and FP1-WM (personal communication 2018, July 3) also confirmed that sourcing LG6 and MG1/2 chromite is costlier in comparison to buying UG2 chrome concentrate and producing sintered pellets (FP1-EM & FP1-WM, personal communication 2018, July 3).

Pelletising and sintering pellets increases the strength of the ore, which reduces attrition during handling and smelting. This in turn decreases fines formation and improves the permeability of carbon monoxide during smelting. Briquettes are prone to decrepitation (breaking-down of ore particles under heat) during smelting, which reduces the porosity of the ore particles, causing fewer recoveries.

It has also been noted that pellets require less electrical energy for smelting. For this reason, sintered pellets are advantageous for their higher metallurgical efficiencies, in addition to their lower energy demands, in comparison to briquettes and conventional lumpy ore (Basson & Daavittila, 2013). In addition, the composition of sintered pellets is more easily controlled, resulting in a more consistent feed, which is preferred when operating a smelter (FP1-EM & FP1-WM, personal communication 2018, July 3).

Logically, it would be expected that with the surge of pellet use, mineral waste intensity would decrease. This is in contrast with the results shown in Figure 4-4, however, whereby the mineral waste produced has remained consistent in comparison to the ore intensity. FP1-EM and FP1-WM (personal communication 2018, July 3) pointed out that around 40% of chromite mined is sold to the market. As a result, the reported mineral waste is not a direct function of ferrochrome production. It was further stated that the mineral waste reported includes slag, slimes, and waste from mining activities.

FP2-WM (personal communication, August 23) could not confirm whether the results reflected those of FP2, because of uncertainty pertaining to the accounting methods. Notwithstanding this, it was mentioned that the industry had similar trends. FP2-SS (personal communication 2018, July 16) stated that in terms of mineral waste accounting at FP2, only slag was recorded, i.e. mining and beneficiation waste such as tailings were not.

CF2-Dir (personal communication 2018, October 09) could not confirm the trends, however they stated that the industry accumulated slag due to South African regulatory barriers. These barriers limit the repurposed use of ferrochrome slag due to slag being regarded as hazardous waste. In contrast, CF2-Dir (personal communication 2018, October 09) stated that slag only becomes hazardous when ground up. As the public perception is that slag is hazardous, however, it was argued that ferrochrome producers would be at risk of being perceived as discarding hazardous waste in communities if they gave it away for repurposed use. For this reason, ferrochrome producers do not sell slag.

4.2.1.3 Water intensity

Although only Glencore-Merafe's results were shown in the preliminary results, there was consensus amongst the participants that the results reflected those of the industry.

FP2-WM (personal communication, August 23) pointed out that although FP2's water intensity is within the range of the preliminary results, it should be noted that FP2's water intensity was significantly less, especially for the three months prior to the interview. However, FP2's business model is more focused on production activities than mining activities. FP1-EM and FP1-WM (personal communication 2018, July 3) highlighted that the preliminary results by Glencore-Merafe included mining activities, i.e. smelter operations alone consume about 2 m^3/ton_{FeCr}, and up to 8m^3/ton_{FeCr} when mining activities are included. Furthermore, some of the ore derived from the mining activities is sold, which increases the amount of water the company consumes to produce a unit of ferrochrome.

FP1-EM and FP1-WM (personal communication 2018, July 3) stated that FP1 has intensified its water recycling measures, in addition to constructing and lining more dams and underground water canals. Consequentially, the company is drawing less water from the environment.

4.2.1.4 Energy

Energy intensity results were presented in the preliminary results and classified into direct and indirect energy. It was confirmed that direct energy referred to oil, liquefied petroleum gas (LPGs) and coal, whilst indirect energy referred to electricity from the national grid (FP1-EM & FP1-WM, personal communication 2018, July 3). FP2-SS (personal communication 2018, July 16) stated that FP2 only records indirect energy use data, which is limited to the smelter plant excluding mining activities.

The participants cited numerous known areas that influence electricity intensity, which for individual smelters is around 3.1 to 3.3 kWh/kg_{FeCr} (FP1-EM & FP1-WM, personal communication 2018, July 3).

FP1-EM and FP1-WM (personal communication 2018, July 3) noted that energy intensity fluctuations are caused by numerous factors including production volumes, which are in turn influenced by market variables. Greater production volumes lead to lower energy requirements per unit of ferrochrome produced. Producers, particularly South African producers, cannot dictate market conditions however, and therefore cannot control production volumes.

It was further stated that in 2007 and 2014, Glencore implemented the Lion Project, which was a two-phase ferrochrome plant construction project. Starting up a furnace requires a considerable amount of ore and energy to reach optimal operating conditions, which causes efficiencies to decline as a result. Therefore, it was highly likely that the peaks seen on the preliminary results were because of the implementation of this project.

FP1-EM and FP1-WM (personal communication 2018, July 3) asserted that the specific ferrochrome product or recipe followed also influences electricity intensity. FP2-WM (personal communication, August 23) agreed, adding that ore grade or quality impacts energy intensity. An increase in the concentration of gangue (undesirable material) causes an increase in the intensity of energy because gangue will also be heated and leaves the smelter as waste. Conversely, higher chromium concentrated lumpy ore requires less energy (FP2-WM, personal communication, August 23).

Pellets have raw materials that are proportionally present for optimal smelting conditions. In addition, pellets approximate lumpy ore, which is preferred for smelting. Consequently, more energy is consumed with conventional chromite in comparison to chrome pellets (FP2-WM, personal communication, August 23). To attain higher efficiencies, the industry has moved to increased pellet use (FP1-EM & FP1-WM, personal communication 2018, July 3). FP2, for example, has increased pellet production capacity to fulfil 77% of full production capacity (FP2-WM, personal communication, August 23).

4.2.2 Synthesis interview outcomes

The participants were of the view that the preliminary results are representative of the industry, despite the company specific differences. Production was noted to be influenced by market factors, particularly the price of ferrochrome, as producers increase production with increasing ferrochrome prices. The decreasing chromite intensity was confirmed to be an industry wide trend and not limited to Glencore-Merafe. With reference to the industry, the decline was credited to the wide use of Outokumpu pelletising technology. With respect to Glencore-Merafe, it was attributed to the installation of the more efficient proprietary Premus furnace technology.

The popularity of sintered pellets was also promoted by the resulting reduced energy intensities and overall decreased production costs in terms of securing UG2 chromite. The success of pellets in the industry has resulted in the development of industrially symbiotic K1 and K1.5 facilities. Although chromite intensity decreased, mineral waste production for some companies did not, because the mineral waste production trends reported included mining activities, yet not all ore mined was used in the production of ferrochrome.

Water intensity was also noted to be similar to industry performance. FP2's water intensity was stated to be lower in comparison to the preliminary results, but within range of those results. In terms of the preliminary results, only about 2 to 3 litres/kg$_{\text{FeCr}}$ were from smelter activities, while up to 8 litres/kg$_{\text{FeCr}}$ were attributed to all activities, including mining activities. Furthermore, not all mining activities contributed to the production of ferrochrome, as some of the ore mined was sold to the market.

It was confirmed that direct energy referred to fossil energy sources consumed on site, whilst indirect referred to electricity from the grid. The start-up of furnaces was confirmed to significantly require more resources, while chromite quality, ferrochrome recipe and production volume were all determined to affect energy intensity.

4.3 Industry resource intensity projects

Numerous projects in the industry were reviewed and classified according to the resource intensity affected or optimised. Expert interview results concerning projects in the industry are discussed below, together with the projects, to ascertain what technological improvements have occurred in the ferrochrome industry and the reasons for initiating the projects.

4.3.1 Known projects

Several resource optimisation projects are mentioned throughout this study; a bar graph is shown in Figure 4-8 which shows the number of known ferrochrome industry projects that have been initiated relating to resource intensity optimisation.

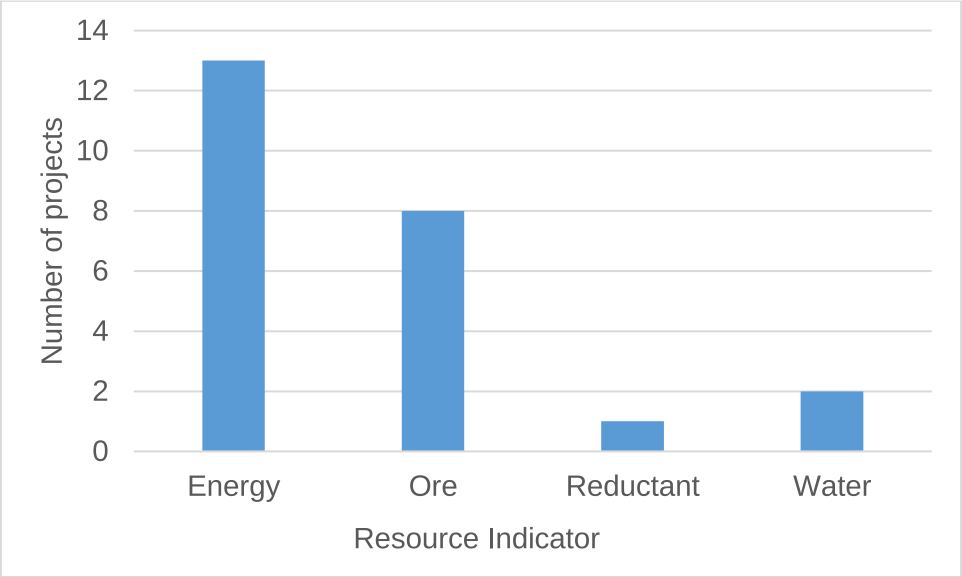

Figure 4-8: Resource optimisation projects with respect to type of resource

Energy related projects were the most pursued, followed by projects related to chromite (mostly pelletising and sintering projects), then water and lastly reductant use. It should be noted that the projects presented in this study were not exhaustive, i.e. they were based on the interviews and publicly available citations. Furthermore, most of the projects optimised more than one resource intensity. For instance, the Glencore Lion Project, which built two Premus technology submerged arc furnaces, was stated to require 37% less energy and less coke to produce a single unit of ferrochrome in comparison to conventional furnaces (Basson, et al., 2007). Premus technology is regarded as the most cost efficient and energy efficient ferrochrome smelting technology in the world (Glencore-Merafe, 2011).

Energy Projects

Around 2007 to 2012 there was a motivation from the South African government for companies to reduce energy consumption, implement cogeneration and utilise electricity buy back schemes. According to CF1-Dir (Personal communication 2018, September 7), for every 100 units of energy consumed in conventional smelting practices, 20 units were lost to the environment. The lost energy takes the form of flue gas as chemical energy (carbon monoxide) and heat energy. Carbon monoxide (CO) has been previously managed by flaring because it is combustible and hazardous to human health.

Several producers have started putting this flue gas back into the process, using some of the following known routes. CF1-Dir (personal communication 2018, September 7) described this in detail (see Appendix B.6.4):

- *Preheating* – Hot furnace flue gas may be used to preheat raw materials being fed into the smelter. This reduces the electrical energy applied to the furnace required to heat and smelt the raw materials.
- *Pre-reduction* – As per section 2.2, this involves the partial reduction of chromite prior to being fed into a submerged arc-smelter. This route has been known to yield energy savings and other cost savings (Dawson & Edwards, 1987). CF1-Dir (personal communication 2018, September 7) noted that numerous ferrometal companies have endeavoured to implement this process route unsuccessfully. For instance, Samancor investigated the prospect but did not pursue it, while Exxaro also attempted to implement this route unsuccessfully.
- *Cogeneration* – CO is conditioned then combusted as a fuel to generate electricity. Calorimetric values of about 10 to 11 MJ/m^3 from the fumes can be expected. Although companies such as IFML have manged to implement this optimisation route, notably, Hernic Ferrochrome explored this route and could not proceed as it hinged on the sale of generated electricity back to the grid, which did not transpire.
- *Sintering* – Heat energy from the high temperature CO flue gas is used to sinter pellets in a rotary kiln, thereby reducing energy requirements and flue gas emissions. This has become common practice in the industry. During furnace start-up and shut-down, propane is used as a fuel due to limited stable CO supply (FP2-WM, personal communication, August 23).

CF1-Dir (personal communication 2018, September 7) pointed out that a combination of these routes can be used simultaneously, depending on the project needs and production dynamics. The industry is also investigating electrodes in furnaces with the goal of reducing electricity consumption.

Although several energy optimisation projects have been explored and implemented in the industry and at FP2, these projects have not significantly realised reductions in energy consumption (FP2-WM, personal communication, August 23).

When comparing the number of projects that involve energy, and particularly electricity intensity in the industry, a significant decrease in energy and electricity intensity could be expected. Nevertheless, the number of projects alone cannot be used indicate the effect of each project on the industry because of the varying nature of application and non-exhaustive results.

Ore projects

Ore efficiency projects include both greenfield and brownfield pelletising and sintering plants. Due to the friable nature of South African chromite, producers have had a limited supply of preferred lumpy ore, leading to the wide acceptance and use of sintering and pelletising technology, as discussed in section 4.2.1.2. This was observed to be an increasing trend, as evidenced by Anglo American Platinum's (2019) (a PGMs production company) investment into chrome concentration plant expansions as a business strategy focus, as per their company operations overview report.

A good of example of chrome concentration production from a PGM UG2 beneficiation operation can be found at K1 and K1.5 concentrator processing plants located in Kroondal, Rustenburg. Figure 4-9 shows K1 on the map.

Figure 4-9: Location of K1 Mine in Rustenburg, South Africa (Google Maps, 2019)

K1 is operated by Sibanye Stillwater, a UG2 PGM concentrator in the Western limb of the Bushveld Complex. K1 receives run of mine and beneficiates the ore for further PGM processing. In the process, tailings with a 20.5% Cr_2O_3 concentration are produced. These tailings are sent to an adjacent chromium concentrator plant called K1.5. In K1.5 the tailings are beneficiated to about 40% Cr_2O_3.This product is used as chrome concentrate to be pelletised and sintered for ferrochrome production. K1 and K1.5 are shown in the satellite image in Figure 4-10.

Figure 4-10: Satellite image of K1 and K1.5 facilities at Kroondal, Rustenburg, South Africa (Google Maps, 2019)

K1 is shown by the yellow block and K1.5 is shown by the red block in Figure 4-10. The use of a waste stream (tailings stream in this case) from one operation as a feed stream for another process could be an indication of industrial symbiosis. Industrial symbiosis has been defined as a means of resource optimisation, whereby traditionally separate but co-located industries exchange by-products and/or utilities for a mutually competitive advantage (Jacobson, 2006).

The features of industrial symbiosis are present in the K1 and K1.5 case. Economic gain is recognised as a feature of industrial symbiosis by Jacobson (2006); in this case, K1 receives financial gain from the mass transfer and reduces waste management. This, together with the benefits to the ferrochrome industry, has led to the surge in chrome concentrate seen in Figure 4-3.

Water intensity

Two reported water use optimisation projects were discovered while conducting this study. These focused on installing water treatment facilities and applying concrete on canals and storm water drains to prevent water losses to the environment.

Reductant intensity

Only the Lion Project was found to optimise reductant use. It should be noted that coke consumption reduction was cited, and not necessarily overall reductant consumption (Glencore-Merafe, 2017).

All in all, energy projects were found to be the most pursued, especially with projects relating to flue gas use. Ore optimisation projects were centred around greenfield and brownfield pelletising, while water projects were focused on water treatment facilities and concrete application on water networks. The only reductant project was related to the Lion Project.

4.3.2 Project drivers

This section outlines some of the motivations behind the projects discussed in the previous section.

4.3.2.1 Economic drivers

Remaining profitable

Financial viability was the most common reason given for the initiatives, as implementing eco-efficiency improvement projects often translates to less maintenance and improved productivity, which results in cost reductions (FP1-EM & FP1-WM, personal communication 2018, July 3; FP2-SS, personal communication 2018, July 16; FP2-WM, personal communication, August 23). FP1-EM and FP1-WM (Personal communication 2018, July 3) added that companies have a responsibility to use best practices, because if it is published in the media that a company performs poorly in certain aspects, it may affect that company's financial performance. In addition, these initiatives have become necessary to remain competitive in challenging market conditions (FP2-WM, personal communication 2018, August 23; CF2-Dir, personal communication 2018, October 09).

A significant development in the industry has been the increased use of UG2 chrome concentrate from the platinum industry, because it is cheaper than sourcing and processing LG6 and MG1/2 chromite as no mining costs are incurred. LG6 and MG1/2 chromite has higher Cr:Fe ratios than UG2 concentrate, thus it should yield ferrochrome with higher chromium content. As ferrochrome producers are only paid for the chromium in the ferrochrome and not the other ferrochrome components, such as iron, during periods when the price of ferrochrome is low, producers will prioritise processing UG2 chrome concentrate. Conversely, when the price is high, the cost of processing LG6 and MG1/2 is justified (Cramer, et al., 2004).

Producers are also confronted with a choice between expensive coke and other cheaper reductants such as anthracite. This is because, in addition to being expensive, the coke supply is limited and sometimes must be imported. This is evidenced by IFML (2015), which imported coke when the price of coke increased and the quality of South African coke declined. The choice of reductant also affects emissions as anthracite has a higher FeS_2 content than coke, and consequently produces higher SOx emissions. Since anthracite is cheaper than coke, it then becomes a choice between financial and environmental merits.

For instance, the country's reductant supply was previously enough to meet local demand, but has recently been insufficient, necessitating importation. The increase of ferro alloy production, coupled with stagnant coke production capacity, are the causes for these supply concerns. Within the ferrochrome industry, there has been a growing preference for closed furnaces because of the advantages relating to environmental impact mitigation. The disadvantage of these furnaces, however, is that they require more coke (0.31-.33 specific consumption), which compounds the coke supply concerns (Basson, et al., 2007).

Increasing electricity prices

The increasing price of electricity and its consequential negative effect on profitability in the industry has motivated efficiency improvements projects (CF2-Dir, personal communication 2018, October 09). From around 2007 there was a lot of activity in the industry regarding the reduction of electricity consumption and emission reduction through cogeneration, however some of these projects were not completed (FP1-EM & FP1-WM, personal communication 2018, July 3; FP2-SS, personal communication 2018, July 16). IFML is one of the companies that has completed a project. With the stated intention of generating 11% of the company's annual electricity requirements through a cogeneration plant, construction started in 2009, and in 2011 the plant was said to be operating at 65% capacity (IFML, 2011).

The high cost of electricity has directed producers to opt for closed furnaces, because these allow for flue gas to be used for other energy requirements in the process. In addition, these furnaces operate at relatively low off-gas temperatures in comparison to open DC arc furnaces. Furthermore, closed furnaces allow for the improved management of emissions into the environment. Although reaction kinematics and thermodynamics are improved in open furnaces (Cramer, et al., 2004), under the current conditions, electrical energy reduction gains outweigh the benefits of open furnaces.

Carbon Tax

The South African government has been planning to introduce a carbon tax, which the industry has been preparing for by working towards reducing emissions (CF1-Dir, personal communication 2018, September 7). The carbon tax has been a significant driver towards reducing carbon emissions, and has been the impetus for various extensive research and development projects in the industry (FP2-SS, personal communication 2018, July 16).

Market cycles

Market cycles have been noted to significantly influence whether projects are profitable (CF1-Dir, personal communication 2018, September 7), for example the ferrochromium commodity cycle has been credited with inhibiting the full development of technology due to periods of unfavourable economic conditions (Basson, et al., 2007). The choice of exploiting LG6 and MG1/2 seams for sourcing chromite, as opposed to UG2 chrome concentrate, is significantly influenced by the price of ferrochrome (Cramer, et al., 2004).

Carbon credits

The prevalence of carbon credits in the early 2000s was influential to the initiation of efficiency improvements in the industry. These credits were accumulated by demonstrating that a project was introduced that reduced carbon emissions. Credits earned could be sold to the open market, with the price being market-based. The price of a credit reached around 6 euros per tonne of CO_2, which meant that price projects could be financially justified (CF1-Dir, personal communication 2018, September 7).

Around 2005 the price of carbon credits started to decrease, however, until the projects could no longer be justified. During the period that the credits had an appreciable price, the industry undertook significant measures to reduce emissions. These credits could thus be criticised for facilitating payment for the implementation of best practice, i.e. companies did not pursue best practice independently (CF1-Dir, personal communication 2018, September 7).

4.3.2.2 Legislative drivers

Legal compliance and public expectation

CF2-Dir (Personal communication 2018, October 09) attributed most of these endeavours to legal compliance requirements. FP2-WM (personal communication, August 23) was also of the view that companies are obliged to be legally compliant. Moreover, FP1-EM and FP1-WM (Personal communication 2018, July 3) stated that FP1 strives to perform beyond legal compliance to be in a better position to receive changes in legislation. Notably, Hernic Ferrochrome successfully converted two semi-closed furnaces to closed furnaces, resulting in reduced particulate matter atmospheric emissions and thermodynamic efficiencies (Hernic Ferrochrome, 2017).

Global warming imperative

The awareness of greenhouse gases and global climate change contributions by the industry, despite minimal regulatory expectations, has become a matter driven by moral and ethical concern (FP1-EM & FP1-WM, personal communication 2018, July 3; CF1-Dir, personal communication 2018, September 7).

According to FP1-EM and FP1-WM (Personal communication 2018, July 3), moving towards sustainability in the South African industry is the responsibility of each company. Multinational companies and high production volume companies are open to international scrutiny and must adhere to domestic and international standards, however companies that only operate on a small scale are somewhat exempt from these expectations. FP2-WM (personal communication, August 23) added that environmental management expectations are not strict as the market is mostly based in China and Europe, which do levy significant penalties.

FP2-WM (personal communication, August 23), however, asserted that the industry is aware of its social corporate responsibility, noting that the Ferrochrome Producers Association (FAPA) shares information pertaining to legislation, reporting, initiatives, and health and safety. Furthermore, resource management has become too significant to be ignored by a company that aims to remain competitive.

The conversion of two semi-closed furnaces into closed furnaces in 2009 by Hernic Ferrochrome can be seen as a proactive decision with regards to environmental impact management, as semi-closed furnaces expose process material to the atmosphere (Hernic Ferrochrome, 2017). In closed furnaces, air does not feature significantly with the raw materials. In addition, gas fumes from smelting are captured and not released to the atmosphere without being treated or incinerated (Cramer, et al., 2004). The mitigation of greenhouse gas emissions contributions towards the imperative to manage global warming.

Regulatory inconsistency and barriers

Whilst it has been noted by the experts that legislation has promoted efficiency improvements in the industry, there have been instances where legislation was a hindrance. Some projects have required substantial inputs in terms of time and money, yet the government has not always completed programmes, meaning companies have lost out on their investments. For example, the Integrated Resource Plan by the Department of Energy promoted the purchase of cogenerated electricity, yet this was never finalised (CF1-Dir, personal communication 2018, September 7).

The use of ferrochrome slag in various applications, including construction, is well documented, however in South Africa it is regarded as hazardous waste. Basson et al. (2007) noted that South Africa has adopted legislation which is better suited for developed countries, particularly in relation to the disposal of dust and slag. Given that there is a perception that slag is a waste, it is perceived as waste being dumped into communities, thus the option of virgin materials is preferred over slag (CF2-Dir, personal communication 2018, October 09).

The advantages of using slag include less greenhouse gas emissions, a reduction in the use of virgin materials, as well as fewer resources needed to produce the materials. At times slag also has superior functionality, particularly in civil engineering and manufacturing applications (CF2-Dir, personal communication 2018, October 09).

Similarly, a Clean Development Mechanism (CDM) for Hernic Ferrochrome, which aimed to produce electricity from waste gas (cogeneration), was not pursued because the success of the project hinged upon the Cogeneration Feed-In Tariff (COFIT) programme and certified emissions reductions revenue. There were uncertainties about the COFIT programme as cogeneration was considered to be a non-renewable source of energy (Fritz, 2012), thus the project was eventually shelved due to the uncertainty (CF1-Dir, personal communication 2018, September 7). In 2017, Hernic Ferrochrome applied for business rescue (Hernic Ferrochrome, 2017) but there was no mention of cogeneration in the business rescue plan (Hernic Ferrochrome, 2018). The program ultimately affected the financial viability of the project and the uncertainties of the resulted in the project being suspended.

Summary

The participants were of the view that resource efficiency in the industry is improving because the cost of mining is increasing; producers are therefore compelled to investigate and implement cost reduction measures which coincide with improvements in resource efficiency. Although emissions were not within the scope of this study, it was noted that emissions reductions were caused by cost reduction measures and regulatory operating standards.

4.4 Discussion of results

The previous section shows the results of this study, which are discussed in this section with the aim of answering the research questions.

4.4.1 How has the ore yield changed over time?

The first research question concerned the trend of ore grade being used in South African ferrochrome production. Ore grade trends could not be obtained because of limited available data, however production, ore intensity, UG2 concentrate production and mineral waste intensity trends were compiled.

It was deduced from Figure 4-1 that industry production has increased over time, although with occasional fluctuations. Moreover, ore intensity (Figure 4-2) was noted to be decreasing, whilst UG2 chrome concentrate from PGM tailings to the ferrochrome industry (Figure 4-3) has increased.

In addition, the Cr:Fe ratio was stated as the most indicative measure of grade. It has been shown that the intake of UG2 concentrate with inherently lower ratios than LG6 and MG1/2 has increased due to numerous operational benefits. This means that fewer LG6 and MG1/2 seams which had higher Cr:Fe ratios were being exploited for ferrochrome production. Notwithstanding this, sintered pellets were shown to yield better chromium recoveries in comparison to conventional lumpy ore and fine ore, due to agglomeration and greater particle strength.

If Cr:Fe is regarded as the main indicator for ore grade, it was inferred that ore grade of consumed ore has decreased, with increasing UG2 chrome concentrate consumption in the ferrochrome industry. FP2-WM (personal communication, August 23) also asserted that the ore grade of chromite in the industry has decreased. Therefore, in answering the research question, the ore grade trends could not be confirmed, however it was inferred that the ore grade has decreased. Despite this, the quality of ore has improved due to pelletising and sintering, which has improved the cold strength and hot strength of pellets, significantly reducing losses during handling and smelting.

4.4.2 How have the resource intensity trends of ferrochrome production in South African changed over time?

The second research question was answered by discussing the compiled resource intensity trends in conjunction with the interview results.

Ore

Ore intensity was found to have decreased over time. This was attributed to the improvement in efficiencies brought about by the ubiquitous application of pelletisation and sintering in the industry. Pelletising enables the agglomeration of fine ore, which is preferred for smelting as it promotes the permeability of carbon monoxide. In addition, sintering enhances pellet strength to withstand attrition during handling and smelting, which in turn limits the formation of fines. The combination of these attributes results in improved metallurgical efficiencies, and, accordingly, decreased ore intensity.

Water

Pertaining to water intensity trends, three companies' results were compiled as shown in Figure 4-5. Glencore-Merafe's water intesity was greater than that of IFML and B2, as B2's scope was limited to post mining and beneficiation results, whilst the Glencore-Merafe results included mining and beneficiation. When compared to the results from an ICDA study, Glencore-Merafe's water intensity results were higher. On the other hand, the IFML and B2 results showed a smaller difference in magnitude when compared to the ICDA study results.

It is worth noting that Glencore-Merafe's water accounting includes water that was used in mining for chromite sold to the market without being processed further by the company for ferrochrome production. In addition, water intensity trends were sensitive to occasional operational changes, such as the starting up of furnaces which led to spikes in the trends.

It was also mentioned that water accounting methods changed in 2012. Furthermore, only two years' worth of water usage from B2 and IFML could be accessed, thus water intensity trends could not be decisively stated. However, if water accounting methods are assumed to have been consistent between 2012 and 2017, then water intensity can be regarded to have decreased by 31%.

Energy and electricity

Energy intensity trends were presented as direct and indirect energy sources, with indirect energy intensity trends (electricity) being notably greater than direct energy intensity trends. In addition, electricity intensity gradually decreased over time, but there were no discernible changes regarding the direct energy intensity trend. Between 2007 and 2017, electrical energy intensity decreased by 14.5% in Glencore-Merafe, while IFML reported a significant decrease between 2010 and 2011 due to improvements in technology. It can thus be concluded that electrical intensity decreased.

Reductant

The Lion Project was the only project that alluded to a reduction in reductant intensity. Nevertheless, as trends were not compiled in this study, it cannot be confirmed whether there have been changes in the consumption of reductants and whether any new technologies have caused changes in reductant intensity.

4.4.3 What has the impact of technological changes been on resource intensity trends?

The technology that led to changes noted in the previous section are discussed in this section.

Ore

The introduction of agglomeration and sintering technology by Outokumpu into the industry has allowed the use of LG6 and MG1/2 chromite fines and UG2 chrome concentrate for ferrochrome production. As noted in previous sections, PGM tailings are concentrated to increase the chromium content, then agglomerated into pellets and sintered in preparation for smelting.

Sintered pellet use has become well received in the industry, leading to a case of industrial symbiosis in Kroondal (see Figure 4-9 and Figure 4-10). K1 is a PGM concentration facility which beneficiates PGM runoff and sends tailings to the co-located K1.5 chromium concentration facility, which beneficiates the PGM tailings to chrome concentrate which is used in ferrochrome production. Furthermore, PGM companies recognise that chromite concentration plants are strategic future objectives. All these advancements have led to the significant decrease of ore intensity noted in this study.

Water

Water intensity could not be concluded definitively, nevertheless notable decreases in water intensity were observed. Water optimisation projects were cited as the main contributing factor to the reduction intensities, including the application of concrete on dams and water canals, and increased recycling.

Energy

There have been reductions in electrical intensity in the industry following the implementation of various technologies. Energy intensity reduction projects were found to be the most common in this study, however it was noted that greater reductions were expected than were actually achieved, owing to the limited extent of investment and research into reducing intensity.

The industry has also moved towards closed furnaces instead of open and semi-closed furnaces, as closed furnaces make it possible to use hot flue gas, which is rich in carbon monoxide, for energy integration in the process. This gas has various electrical energy intensity reduction applications, as noted by CF1-Dir (Personal communication 2018, September 7).

The application of flue gas includes sintering pellets, preheating the furnace feed, pre-reduction and cogeneration. In addition, pellet use results in less overall energy intensity due to less gangue entering the smelter. The extent of the effect of sintering and pelletising on electricity intensity was seen in 2014, when electricity intensity increased both in Glencore-Merafe and IFML when the supply of UG2 concentrate was inconsistent, i.e. less sintered pellets could be produced for ferrochrome production. IFML reported a decrease in electricity intensity following the implementation of cogeneration technology in 2011, which can be seen in Figure 4-7. Premus furnace technology was stated as being the most efficient smeltering technology in the world and is used in South Africa.

In addition to technology use, energy intensity was noted to be influenced by the ferrochrome product type (recipe) and production volume. An increase in production volumes led to increases in energy efficiencies. Moreover, operational changes such as starting-up furnaces were noted to cause significant inefficiencies.

4.4.4 What have been the drivers of resource intensity changes?

Influences

Financial viability was found to be the most significant driver, as most of the projects and process optimisation decisions were taken in the interest of remaining profitable. For instance, when the market cycle resulted in a low price for ferrochrome, UG2 chrome concentrates were prioritised. Conversely, when the markets dictated a high ferrochrome price, LG6 and MG1/2 pellets yielded the best profit.

Ferrochrome production has been noted to be energy intensive, with electrical power and fossil fuels being the main sources of energy for the entire process, including sintering and reduction (Neizel, et al., 2010). Increasing electricity prices have propelled the industry to be more efficient (Basson, et al., 2007); at present the cost of electricity and reductants accounts for 30 to 50% of production costs (Pan, 2013). CF1-Dir (personal communication 2018, September 7) and CF2-Dir (personal communication 2018, October 09) both noted that electricity costs significantly influence profitability.

As electricity efficiency projects have become more common, cogeneration, pre-reduction, preheating and sintering of pellets are increasingly being used due to their ability to reduce energy intensity. Government regulations, as well as awareness of climate change and greenhouse gases, were identified as drivers of these projects. These projects ultimately impact the costs that producers incur, which affects profitability. For instance, companies might have to cease operations or incur government fines if they are found to be externalising costs or not managing waste or resources as expected by regulations, and at time, public expectations.

In addition, the pending carbon tax has necessitated that producers revise their production methods, as South Africa’s electrical production capacity is based on fossil fuels, i.e. electricity consumption will increase costs due to the carbon tax. It was also noted that some producers perform well beyond what is mandatory to be better prepared for inevitable changes in legislation.

5. CONCLUSIONS AND RECOMMENDATIONS

To consolidate and conclude this dissertation, the motivation of the study, along with the accompanying research objectives set out in Chapter 1 and the hypothesis developed in Chapter 3, are reviewed in this final chapter. The key findings discussed in Chapter 4 are then assessed to test the validity of the hypothesis, after which recommendations for policy and industry, as well as for further research, are presented.

5.1 Research motivation

Approximately 80% of the world's chromite reserves can be found in South Africa. Chromite is the most viable raw material for manufacturing ferrochrome, which is used for manufacturing stainless steel. In recognition of the mineral reserves that South Africa bears, the South African government identified that the chrome and stainless steel value chains (amongst other identified mineral value chains) must be developed to harness their potential benefits in order to support the country's socio-economic goals. This is to be achieved through advancing mineral processing of mineral resources.

It has been argued that developing resources further down into the value chain is often chosen as a development strategy based on flawed logic and anecdotal evidence, as opposed to systematic analysis. Furthermore, it has been put forward that there is a lack of understanding regarding the environmental impacts of mining and developing domestic mineral value chains, and the associated mitigation technologies pertaining to mineral resource development. Accordingly, this study set out to systematically improve the understanding of the ferrochrome industry in South Africa and the technologies surrounding those environmental impacts.

5.2 Objectives and major findings

The following were the objectives of the study:

i. To analyse resource intensity trends for the South African ferrochrome industry with the aim of determining the impact of ferrochrome production in South Africa.
ii. To understand the influence of the technological and process changes on the resource intensity trends.

The first objective was achieved through a desktop study for sustainability data, which were used to calculate resource intensities and subsequently develop trends. Company sustainability reports were used as the main source of data, however one of the companies reviewed aided the study by contributing its internal sustainability data. The second objective was fulfilled by interviewing experts in the industry and through event history analysis (EHA). The interviews were semi-structured and aimed to gain insights into major industry projects pertaining to their effect on resource intensity trends. Concerning EHA, a desktop study to identify and catalogue sustainability projects to discern the effect of the projects on resource intensities was conducted.

5.3 Key findings

In determining the resource intensity trends, the ore grade trends also had to be determined. Prior studies were aimed at investigating the environmental impacts of processing various mineral resources, with most studies concluding that ore grade gradually declines over time, causing resource intensities to increase.

For this study ore grade trends could not be determined, however it was noted that there was an increase in the use of UG2 chrome concentrate from the platinum industry. UG2 concentrate is of lower ore grade than chromite concentrate sourced from MG1/2 and LG6 seams, which have been the conventional source of chrome for the ferrochrome industry.

Even though UG2 chrome concentrate may have lower concentrations of chromium, the advent of pelletising and sintering technology has enabled the production of UG2 sintered pellets to have cold strength and hot strength, which minimises losses of chromium during handling and smelting. On the other hand, MG1/2 and LG6 chromite which is known to be brittle (unless similarly agglomerated), which causes losses during handling and smelting.

Furthermore, as UG2 chrome concentrate is sourced from the tailings of the platinum industry, it is cheaper for ferrochrome manufacturers in some instances to use UG2 concentrate, as opposed to bearing the costs of mining associated with MG1/2 and LG6.

There has thus been an increase in UG2 chrome concentrate usage in the South African ferrochrome industry due to the advantages stated above. On account of this, it can be inferred that the chromium concentration of feedstock may be decreasing. On the other hand, the strength of the chromium feedstock has increased, which has improved efficiencies.

Ore intensity trends between 2007 and 2017 were observed to decrease by 20% largely due to the increased UG2 chrome concentrate sintered pellet use. The utilisation of chrome concentrate in ferrochrome production has progressed to the practice of industrial symbiosis, whereby a PGM ore processing plant produces tailings which are sent to a co-located chromium concentration plant. The product from the chrome concentration plant is then sent to a ferrochrome production site for further processing. Ore yield increased over time.

Electricity intensity trends were also observed to have decreased, in part due to the improvement in ore quality, resulting in less feedstock being processed per unit of ferrochrome. In addition, the increased use of closed furnaces, which has enabled energy integration in ferrochrome production, was noted to result in reduced electricity intensity. Heat integration in ferrochrome production occurs when hot carbon monoxide rich gas from smelting is used to preheat furnace feed and pre-reduce smelting feed, reducing electricity requirements. The gas can also be combusted to generate electricity, which reduces the amount of electricity purchased from the national electricity grid. This has led to the conversion of semi-closed furnaces to closed furnaces by one of the ferrochrome South African producers. Another producer reported a decrease of approximately 10% in electricity intensity from the national electricity grid, owing to the combustion of hot smelting gas to produce electricity.

Water intensity trends were obtained, however there was no definitive observed trend or trajectory that could be discerned over the period investigated, as changing water reporting methods hindered an analysis of the trends. However, data for one company post 2012 showed that their water intensity was decreasing. This was attributed to preservation projects within the company such as increased recycling, and the application of concrete to water canals and dam walls.

These types of projects have been influenced by several factors, including cost reduction, legislation, public expectations and organisational cultural shifts to adopt best practice. The price of South African electricity has increased to such an extent that producers have been compelled to investigate and implement electricity reduction projects to remain profitable. Electricity costs contribute up to 50% of production costs (as shown in section 4.3.2), i.e. they have a significant effect on the profitability of an operation.

Government plans to purchase electricity generated from the combustion of carbon monoxide rich gas prompted some ferrochrome producers to investigate and install technology to produce electricity, however the government did not complete their plans, causing some producers to abandon their projects to install these technologies. In this way government has a role to play in technological innovation.

Furthermore, the expectation of the implementation of a carbon tax meant that producers needed to prepare their production processes to minimise potential tax payments. For this reason, the reduction of electricity intensity from the national grid (which is largely reliant on carbon-based energy sources) was more urgent and pertinent to sustainable production.

Producers have also had to adopt best practice production methods to promote sustainable production due to public expectations. The public, the state and producers are becoming increasingly aware of global climate change and greenhouse gases, therefore company operations must be in line with some of the expectations of stakeholders.

5.4 Validation of the hypothesis

This study investigated the following hypothesis:

- The resource intensity would increase over time due to declining ore yield over time. This may be offset with the implementation of technological innovations and differences in processing in the industry.

Based on the key findings it can be inferred that ore grade has been decreasing, which supports the hypothesis, however the strength of pelletised and sintered ore concentrate has increased, resulting in improved efficiencies. This improvement in strength has been achieved though the pelletising and sintering of chrome concentrate, which has led to improved efficiencies in the form of decreased ore losses during handling and smelting. Therefore, whilst the hypothesis guided the research, the unexpected finding of industrial symbiosis practices on a significant scale means that irrespective of trends in grade of mined chromite ore, the industry has been able to generate its product from a smaller amount of mined ore. Therefore, the ore yield has increased.

The improvements in pelletising and sintering technology have led to additional improvements in ore intensity because less raw material is now required to produce a unit of ferrochrome due to reduced losses of fines. Electricity intensity trends were seen to decline, partly due to pelletising and sintering. Pelletising and sintering increases the strength of pellets during handling and sintering resulting in increased recoveries and decreased losses leading to lower energy intensity. Other innovations such as the use of closed furnaces, the preheating of smelting feed, pre-reduction and cogeneration have resulted in reduced electricity intensity from the grid.

Water intensity trends could not be definitively established due to a change in water accounting and reporting. The companies investigated did report a reduction in water consumption and water intensity, however, which was attributed to more vigorous recycling and the application of concrete on dams and water canals.

The second part of the hypothesis, which pertains to the implementation of novel technologies, is thus supported by the evidence, with reported trends explained and supported by the findings of the event analysis and the interview evidence.

The research thus finds that there has been a decoupling of intensity and production.

5.5 Recommendations

Having presented the findings and the conclusion, the resulting recommendations of this study are discussed in this section.

5.5.1 Recommendation for stakeholders

Novel technologies do contribute towards reducing resource intensity trends, with the increased use of sintered pellets from UG2 chrome concentrate reducing resource intensity, including electricity intensity. It is thus recommended that this UG2 chromium concentrate be used in the ferrochrome industry. Furthermore, the establishment of industrial symbiosis, such as that seen between the PGM and ferrochrome industry in section 4.2.1.2, is recommended because of the improvements that were created.

It is recommended that more closed furnaces be used, and that advantageous process options such as heat integration and cogeneration be exploited more to reduce electricity intensity from the grid. This is particularly important due to the profitability of ferrochrome production in relation to the increasing price of electricity from the South African national grid.

Water intensity trends could not be confirmed for the entire period under review, however it was noted that water preservation measures such as lining dams and canals with cement significantly contributed to a decrease in water intensity. It is thus recommended that more dams and canals be lined with cement.

The state’s plan to purchase electricity from cogeneration gave rise to ferrochrome producers either investigating or implementing cogeneration equipment. Although some producers ceased these projects when the plans by the state did not materialise, there has been a considerable reduction in electricity intensity from those cogeneration projects that were completed. For this reason, it is recommended that more consultations between the state and producers regarding resource intensities are facilitated.

5.5.2 Further research

The study relied on the availability of publicly reported data, however these data were largely aggregated across the operations companies. Therefore, if site specific data are obtainable, it is recommended that these be used to compile resource intensity trends, as the effect of production changes can be better compared to the site-specific trends.

In this study, it was inferred that the chromium concentration of ferrochrome production feedstock is decreasing. It would thus be interesting to examine the feedstock to determine if there is a decrease, and the extent to which any decrease has occurred.

It might be interesting to extend this research to pollution intensity trends. Carbon footprint intensity is particularly noteworthy, because this is partly influenced by electricity intensity from the national grid, which has been shown to be decreasing. Furthermore, the outcome may better inform the discussion around the carbon tax.

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Appendix A Overview

Some of the resources used in this study that were not included in the main dissertation have been included in this section. This includes the hand calculations. Supporting interview documents have been included in Appendix B.

A.1 Calculations

The calculations used in this study are shown in this section.

Resource intensity sample calculation

A sample calculation for resource intensity using sample data is shown to demonstrate how it was executed using the resource intensity equation.

$$Resource\ intensity_i = \frac{total\ kg\ of\ resource\ consumed_i}{total\ ferrochrome\ produced_i}$$

The example shown concerns water intensity. Water consumption by Glencore-Merafe was reported to be 11,750 Ml in 2009, whilst total ferrochrome production was 0.98 Mt for the same year. This works out to 11.9 litres/kgFeCr in 2009 for water intensity using the equation above.

Water intensity by Gediga and Russ (2007)

Water intensity for ferrochrome production at various stages of production was reported from the study by Gediga and Russ (2007). The total water intensity was calculated for comparison to this study. An assumption was made that production would be from underground mining with a closed furnace with preheating. Average values were from the study were used.

Table B-1: Total water intensity (Gediga & Russ, 2007)

Production activity	Water intensity $litre_{water}/kg_{FeCr}$
Mining	5.56
Beneficiation	2.82
Smelting (closed furnace with preheating)	4.62
Total	13.0

Power consumption

Power consumption intensities from the study were also used for comparison with this study.

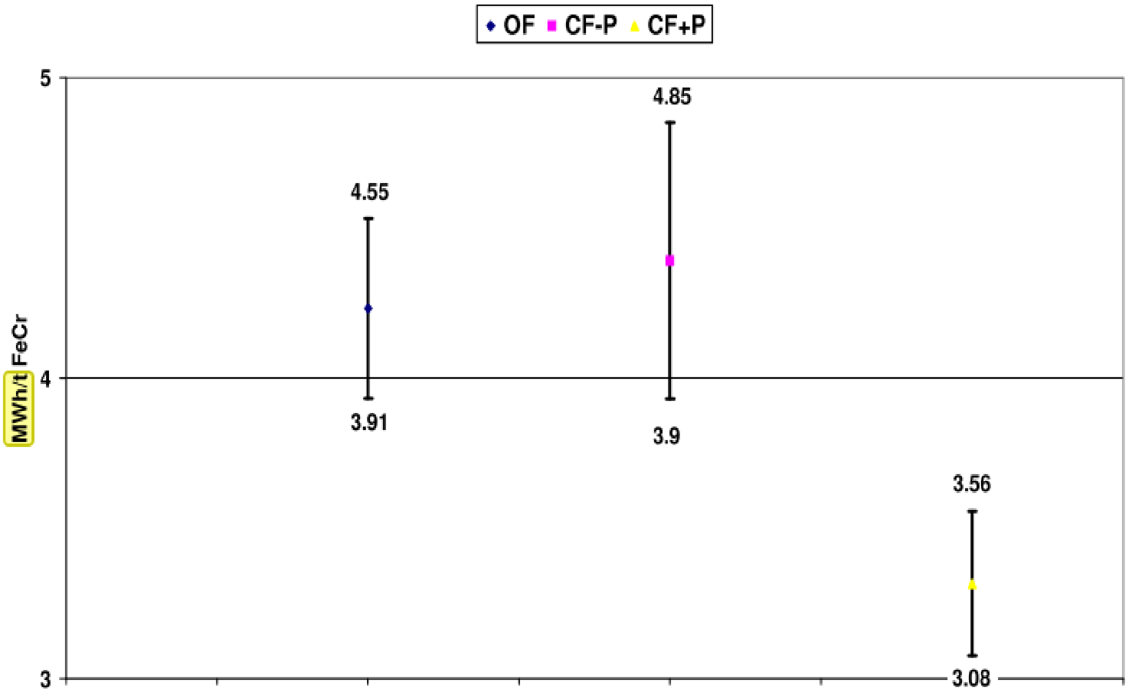


Figure B-1: Average specific power intenisties for the different furnace types in MWh per ton of ferrochrome (Gediga & Russ, 2007)

B.2.

Appendix B Expert Interviews

This section includes the resources used for the expert interviews mentioned. This includes the email used to request the interviews, the consent form signed by the participants, the preliminary results and the ethics clearance approval.

B.1 Email

Dear (*Name of potential interviewee*)

I hope this email finds you well. I would to request an interview with you for academic research regarding the technical developments that have transpired in the South African ferrochrome industry. I am a Master of Philosophy student specialising in Sustainable Mineral Resource Development, having completed my undergraduate degree in Chemical Engineering.

My research is focused on characterising resource intensity trends of the ferrochrome industry in South Africa using Life Cycle Inventory (LCI) studies. This includes understanding the technologies and events that have significantly influenced the resource intensity of the industry.

I would to include you in this study by interviewing you on account of (*the participant's skills and experience would be included in this section*). I think you would make an appreciable contribution towards my research.

The interview would include a briefing and require you to sign a consent form. Subsequently the interview, which would be semi-structured, would commence. Semi-structured implies that the questions which are prepared however these questions are used as guidelines to direct the interview.

If you are available for the interview, the interview should last an hour.

If you have any questions or concerns, please contact me or my supervisor Prof. Harro von Blottnitz who has been copied on this email.

I look forward to your response.

Sincerely,

Reuben

B.2 Consent form

University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

INFORMATION SHEET AND CONSENT FORM

RESOURCE INTENSITY OF THE SOUTH AFRICAN FERROCHROME INDUSTRY

South Africa Ferrochrome Industry and related technical experts

Introduction – Good day. My name is Reuben Dlamini and I am conducting research towards a master's degree. I am investigating resource intensity of the ferrochrome industry in South Africa and would like to invite you to participate in the project.

About the project – The project is aimed investigating some of the major inputs and emissions of the South African ferrochrome industry. This is to establish whether the introduction of technology and declining ore grade have had an impact on the inputs and emissions. I would like to interview technical and industry experts such as sustainability managers and process engineers.

Participation is voluntary - Please understand that you are not obligated and do not have to participate in this project. Your participation is entirely voluntary. The choice to participate is yours alone. If you choose not to participate, there will be no negative consequence. If you choose to participate, but wish to withdraw at any time, you will be free to do so without negative consequence. However, I would be grateful if you would assist me by allowing me to interview you.

Expectations from participants – I will only ask you a few questions regarding the ferrochrome industry of South Africa. This should take 15 to 30 minutes. There is no financial obligation from the project or you as the participant. Therefore there is no payment/reimbursement available. With your permission, I would record this interview however you do not agree that is still acceptable. I also need your consent would like to refer to this recording and any notes I may have taken for academic purposes including my project, academic conferences and possibly journal publications.

Benefits to participant – Please note that there will be no direct or indirect benefit to you as a participant.

Risk of harm to participants – There are no foreseen risks or harm that are presented by choosing to participate or not to participate in this project.

Sharing and use of data – The data generated from the interview will be synthesised and used to answer the research questions set for this masters project, presented in conferences and possibly published in journals.

Anonymity and Confidentiality – The identity of the respondent will be encoded however their standing or position in the industry will be conveyed.

By signing the consent form you agree to the terms stipulated in this consent sheet regarding the interview. If you are not comfortable with the terms please make a note on the form.

Interviewee name:______________________________ Interviewee's signature:_____________

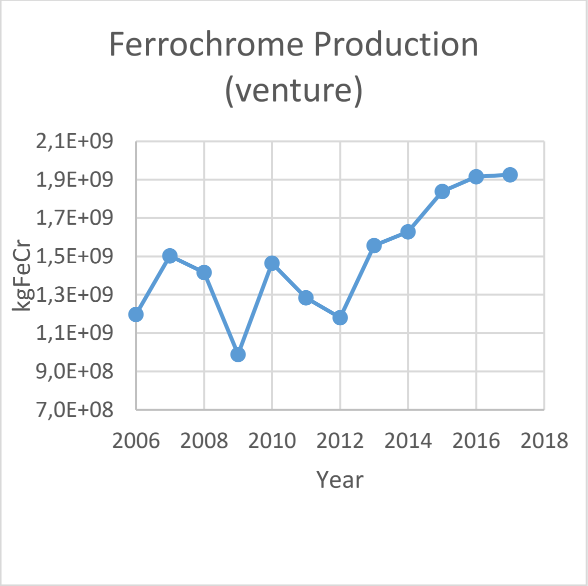
Date:_______________

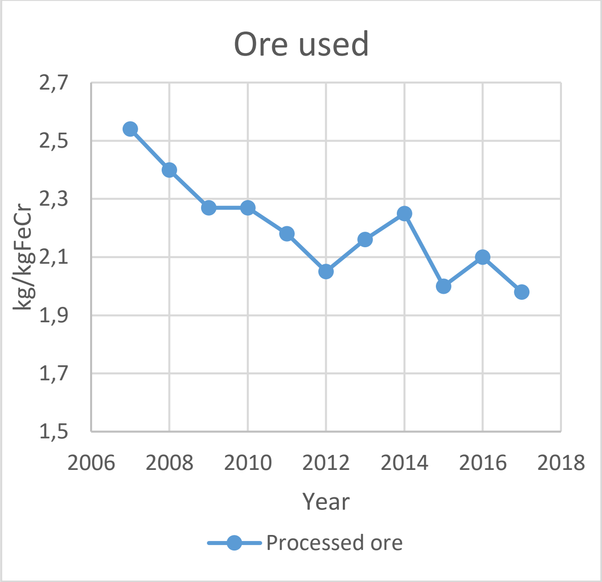
Additional comments

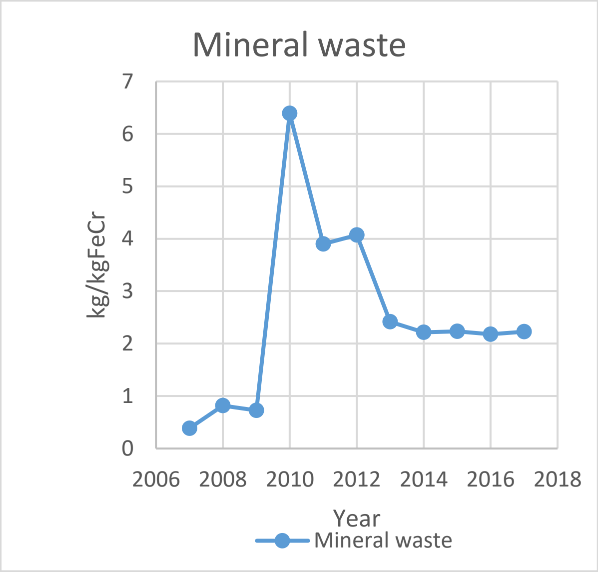
____

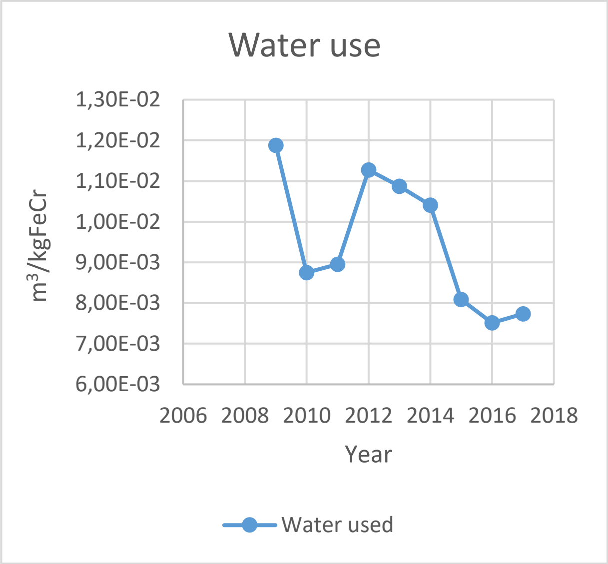
____

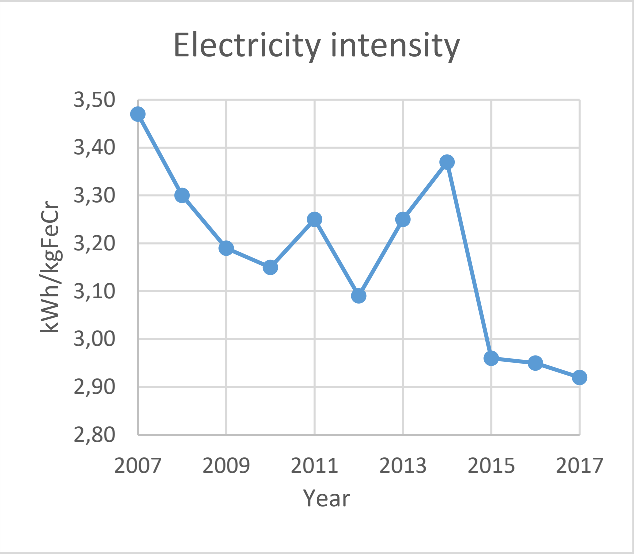
B.3 Preliminary results

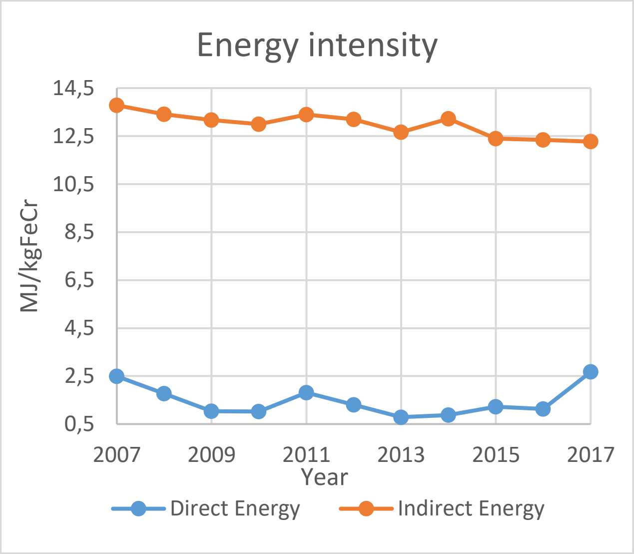


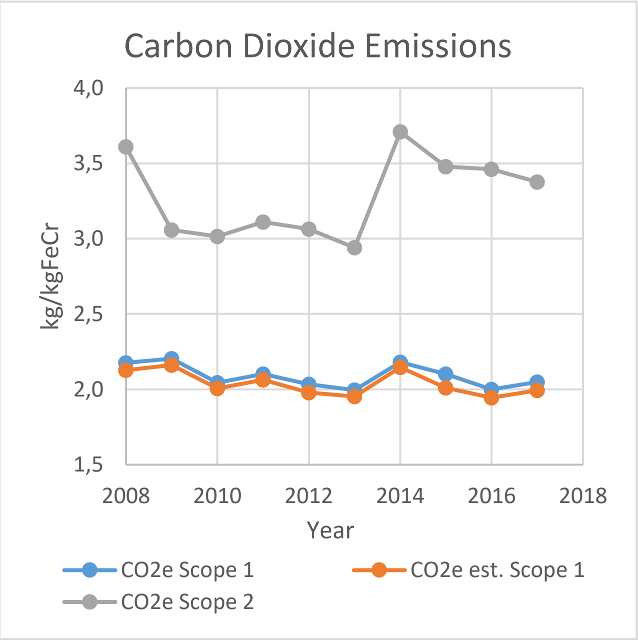


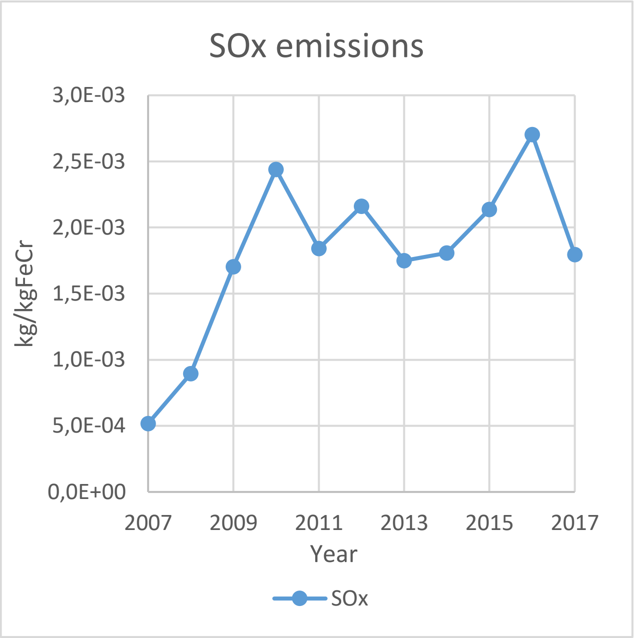


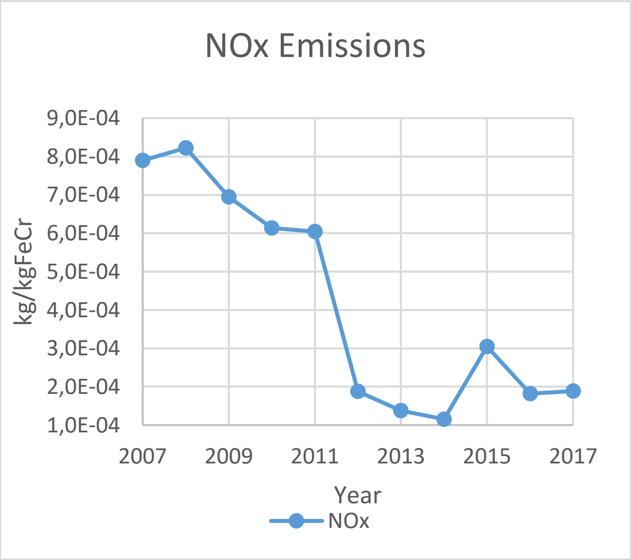



Electricity intensity
kWh/kgFeCr
3,50
3,40
3,30
3,20
3,10
3,00
2,90
2,80
2007
2009
2011
2013
2015
2017
Year


Energy intensity
MJ/kgFeCr
14,5
12,5
10,5
8,5
6,5
4,5
2,5
0,5
2007
2009
2011
2013
2015
2017
Year
Direct Energy
Indirect Energy


Carbon Dioxide Emissions
kg/kgFeCr
4,0
3,5
3,0
2,5
2,0
1,5
2008
2010
2012
2014
2016
2018
Year
CO2e Scope 1
CO2e est. Scope 1
CO2e Scope 2


SOx emissions
kg/kgFeCr
3,0E-03
2,5E-03
2,0E-03
1,5E-03
1,0E-03
5,0E-04
0,0E+00
2007
2009
2011
2013
2015
2017
Year
SOx


NOx Emissions
kg/kgFeCr
9,0E-04
8,0E-04
7,0E-04
6,0E-04
5,0E-04
4,0E-04
3,0E-04
2,0E-04
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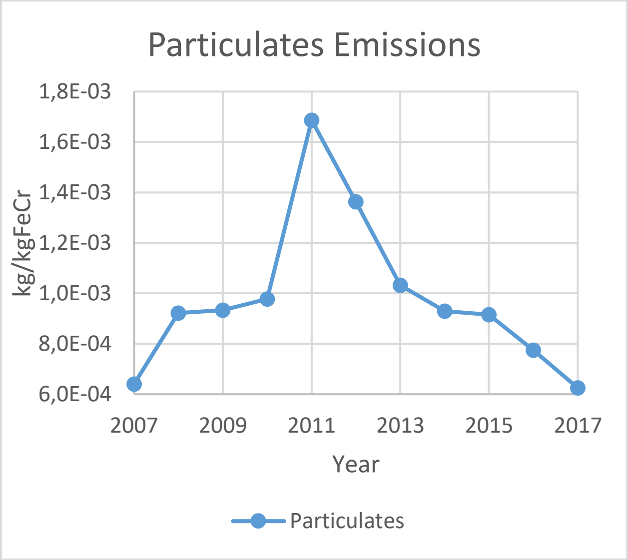
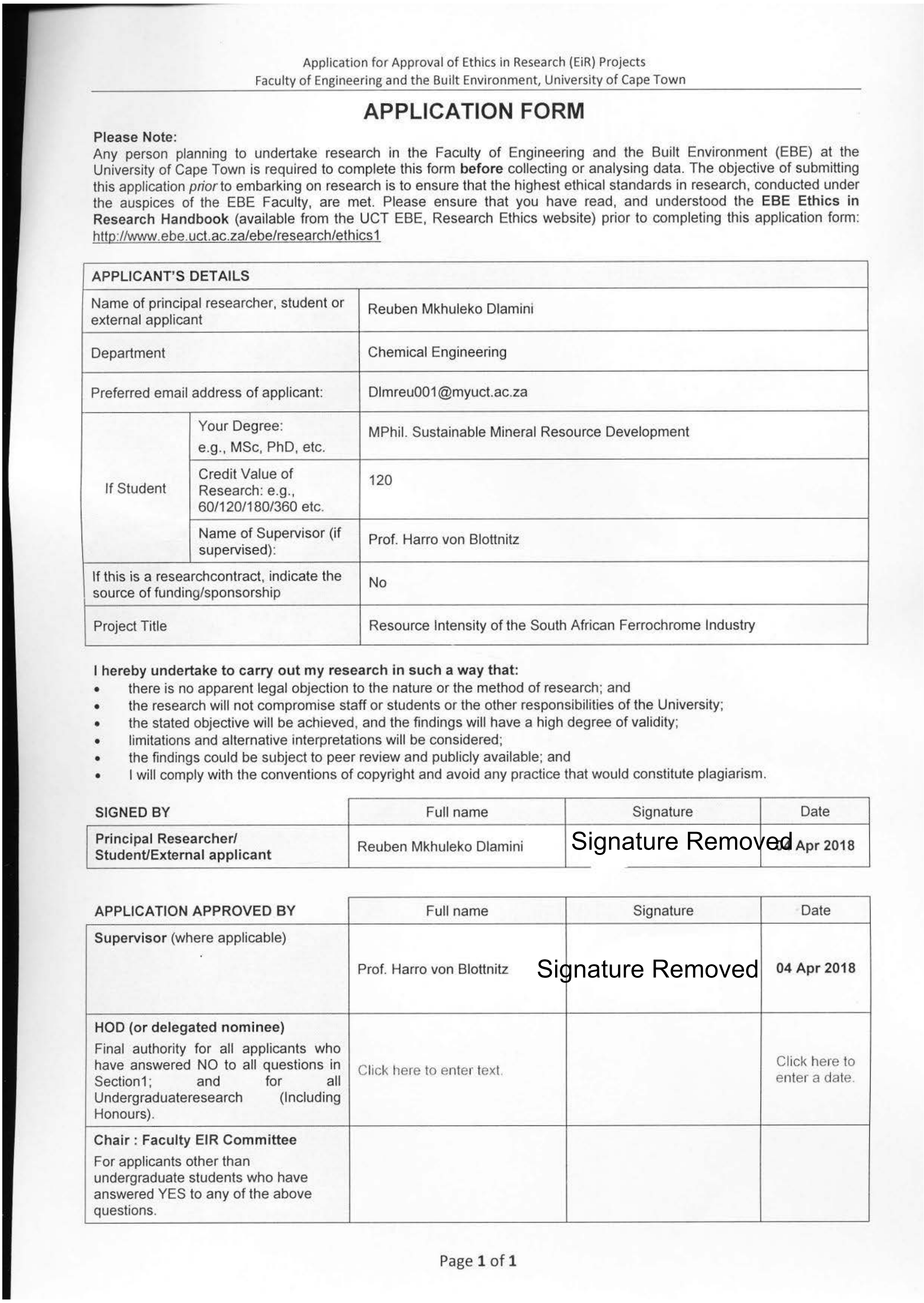
2007
2009
2011
2013
2015
2017
Year
NOx


Particulates Emissions
kg/kgFeCr
1,8E-03
1,6E-03
1,4E-03
1,2E-03
1,0E-03
8,0E-04
6,0E-04
2007
2009
2011
2013
2015
2017
Year
Particulates

B.4 Interview questions

Question no.	Question
1	What is your current position and experience?
2	To your knowledge has there been any new technology or change in operation that has been implemented leading to a change in emissions, output and input of operations regarding ferrochrome production since 2008?
3	What was the reason for the implementation?
4	When was the implementation and is it still in practice?
5	What is the effect or efficiency of this implementation?
6	Which operations have implemented this new technology or change in operation?
7	Do you think eco-efficiency is improving in the industry?
	Additional comments

B.5 Ethical clearance



Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Reuben Mkhuleko Dlamini
Department		Chemical Engineering
Preferred email address of applicant:		Dlmreu001@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	MPhil. Sustainable Mineral Resource Development
	Credit Value of Research: e.g., 60/120/180/360 etc.	120
	Name of Supervisor (if supervised):	Prof. Harro von Blottnitz
If this is a researchcontract, indicate the source of funding/sponsorship		No
Project Title		Resource Intensity of the South African Ferrochrome Industry

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Reuben Mkhuleko Dlamini	Signature Removed	**04 Apr 2018**

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	Prof. Harro von Blottnitz	Signature Removed	**04 Apr 2018**
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section1; and for all Undergraduateresearch (Including Honours).	Click here to enter text.		Click here to enter a date.
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.			

Page **1** of **1**

B.6 Interview transcripts

B.6.1 FP1-EM & FP1-WM

Meta data

Name: FP1-EM & FP1-WM

Organisation: Glencore

Date: 03 July 2018

Time: 1519

Type: Live

Commentary of Results

Ore grade:

FP1-WM: The data trends alright although we do not work with kilograms, we work with tonnes.

R: What would you attribute the decline in ore used per unit of product produced?

FP1-WM: We have improved our efficiencies. We have also introduced (production unit) which one of our biggest contributing factors. We also introduced Outokumpo pelletising plants at three locations.

R: Alright. What about the consistent trend of mineral waste in comparison to the decline use per unit product? Should the mineral waste not be declining also?

FP1-EM: No. You must remember that mineral waste also comes from our mining activities as well. We sell about 40% of the ore that we produce. So, the mineral waste is not just directly linked to ferrochrome production. You have to look at the definition of what mineral waste is. It includes slag, slimes and waste from the mining sites.

FP1-WM: So, ore used per unit product does not include mining activities.

FP1-EM: That assumes that we assumed that all the ore that we consumed goes into the ferrochrome. However, we sell most of it.

R: With regards to the water consumption, I see it fluctuates quite a bit.

FP1-EM: That water also includes water used in mining as well.

FP1-WM: This is far too high for smelters.

FP1-EM: Everything that is reported includes everything that is in ferroalloys. That includes the mines, char plant and so it not just the smelters especially the energy as well.

R: What would you say is the cause of the fluctuations? I am aware that at some point there was a change in water accounting, but I am not sure if that would result in the fluctuations.

FP1-EM: With regards to mines which includes Rhovan which is our vanadium plant, we have started to do a lot recycling with water. We have had this dynamic water processes which has a lot of impact on the way we manage water. So, we recycle a lot of water more. We have also our rainwater collection systems for use in our process. Most of our dam facilities are lined now so all those underground seepages are recovered now. Storm water channels are concrete now. There's a lot of water recovered from that. Because we collect process water and rainwater, we have reduced the amount of top up water that we use.

R: Is that why it is decreasing like it is now.

FP1-WM: The water consumption values that you have are far too low. The smelters alone sit at around 2 m^3 per ton of ferrochrome. That value then most likely includes the mines. However altogether it probably makes around 8 m3 per ton when mines are included.

R: Considering the electricity consumption would you say that those seem plausible?

FP1-WM: These values for electricity are low for the individual average smelter plants. Most of them are at 3.3 and 3.1 kWh/kg_{FeCr}. Also, the production volume affects the electricity that you use because the more ferrochrome produced the less the electricity consumption per unit product.

R: I would like to confirm what is meant by direct and indirect energy?

FP1-EM: Indirect is electricity from the grid and direct is what we consume on site. If we use oil, LPGs and coal that is direct energy. It should include the mine however not the Rowen (vanadium product).

R: What causes the fluctuations in the energy consumption?

FP1-EM: There are many variations and reasons including poor market conditions. Around 2012 and 2014. Around 2014 we commissioned Lion phase two, the furnace will require more ore and electricity per unit product. Furthermore, it takes a while for the furnaces to be calibrated to optimal operating conditions.

R: I understand that the facilities and furnaces are becoming more efficient however I would like to know about the quality of the ore being mined for production?

FP1-WM: When operating a smelter, you need consistency when operating it. That is your feed concentration of chromium must be constant. The biggest contribution to the decline in ore use is the decline of use of lumpy ore to using pellets. Two pelletising plants have since been operating together with the new plant. So, higher capacity plants, coupled with more efficient plant and pellets contributed to the efficiencies. Typically, lumpy ore is more inefficient to process as in comparison to pellets which are easier to process. You need more power to smelt the lumpy rock than the pellet.

FP1-EM: From the UG2 ore you get a chromite ore which is used is a by-product of the PGM. PGM tailings make for easier production of pellets.

R: Please comment on the erratic changes on SOx, NOx and particulate changes as seen from the trends?

FP1-EM: With regards to SOx, NOx and particulates the margins are so small such that differences are so small in terms of values. In addition, the measurements are not exact such that it would no concrete comparisons can be made. We also moved to a new service provider in 2014 or 2015 after realising that the previous company's techniques were not as efficient. It is still a learning process for the company.

R: What has been your current role and experience in the industry?

FP1-WM: 25 years in ferrochrome production with roles ranging from engineering manager, production manager to works manager.

R: To your knowledge has there been any new technology or change in operation that has been implemented leading to a change in emissions, output and input of operations regarding ferrochrome production since 2008?

FP1-WM: Outokumpu tech and Premus tech.

R: What was the reason for the implementations**?**

FP1-WM: To improve efficiencies

When was the implementation and is it still in practise?

FP1-WM: Lion, Wondekorp and Rustenburg smelter.

What was the effect or efficiency of the implementation?

FP1-EM: Less ore use per ton of product and less energy/electricity required per tonne of product

R: Which operations have implemented these new technologies or change in operations?

*This question was skipped since it had already been answered from the previous questions

R: Do you think ecoefficiency is improving in the industry?

FP1-EM: Yes, Carbon monoxide to generate power therefore less impact on the electricity and the impact on the environment is reduced.

Any Additional comments.

FP1-EM: There is a change in the environment. There are a lot of aspects that require us to change. We are always exploring new opportunities to improve further. You always have stay ahead of the times and be adaptive.

We strive to perform beyond what is legally required so that we can be in a position to receive changes in legislation. This is enforced through corporate governance.

The other factors that influence our operations. There is climate change, although it is not a statutory obligation it is an ethical and moral obligation.

There is also a responsibility to that companies must take to use best practise because if it gets publicised in the media that the company performs poorly in certain areas, it will affect the financial performance of the company, investors and all other stakeholders.

With regards to the South African industry moving towards Sustainability, it depends on the company. Our company is a multinational company that has monitored internally and externally. So we have to set the standard and maintain stakeholder relationships as opposed to companies that only operate in South Africa that do not have pressing commitments to the international community.

B.6.2 FP2-SS

Organisation: FP2

Date: 16 July 2018

Time: 16h00 – 17h00

Type of interview: Live interview

Commentary on preliminary results following greetings and introduction.

R: I would to present you these trends and get your opinion on whether they represent what is happening on the ground

FP2-SS: I do not know any of these figures by heart so I would not be in a position to comment at this point. With regards to production we produce in the order of 390 kt per year of ferrochrome. Other I can relay the information to via email.

Waste

FP2-SS: What is included in the mineral waste?

R: It includes all waste from production all the way to the production site.

FP2-SS: We do not have recording system that records all of those things. We only record slag produced per ton of product produced. That excludes tailings and other beneficiation waste.

FP2-SS: Glencore has Premus smelters and we have conventional smelters. Therefore, Glencore consumes less electricity than we do. We are in the region of 4.5 mWh/tFeCr. That is mostly from the furnaces not inclusive of mines.

R: With regards to energy consumption they have differentiated between energy sources from on site and energy sources from the grid the former being direct and the latter being indirect.

FP2-SS: So that would be the LP gas and pulverised fuel. We do not track that.

What has been your current role and experience in the industry?

FP2-SS: Health Safety Development with 9 years' experience in the ferrochrome industry. Master's in Environmental Science.

R: To your knowledge has there been any new technology or change in operation that has been implemented leading to a change in emissions, output and input of operations regarding ferrochrome production since 2008?

FP2-SS: I am aware of cogeneration opportunities where we use furnace offgas, in particular CO gas to produce electricity through using turbines and stem. I know Tubatse has steam however Tubatse has Boshoek at Glencore and at Samancor. That reduces the CO emissions of the smelter and on less electricity consumption from the grid.

We do not use cogeneration, but we did apply for an EIA however we did not execute the project because it did not make financial sense at the time.

We have made a lot of efficiency changes in the scrubber by changing the pump arrangements to increase the pump capacity which in turn increased the water input into the scrubbers which reduced the emissions. Those changes allowed us to operate within our emission licences. So, the pumps were replaced with multistage pumps which increased pressure and flow to the scrubber around 2016-2017.

We also started using Bitumen (bitumen) to on our roads to reduce dust emissions

We have sprayers at all our conveyor transfer points to reduce dust emissions

Slag from ferrochrome manufacturing is sometimes processed further to recover chrome. It is crushed the sent to a flotation station and jigging plant. In the crusher units we have dust suppression sprayers

We also converted two of our semi open furnaces to closed furnaces in 2009. Only operations to have done so in the world. We were then able to change our abatement system from bag system to a venture system. The latter is more efficient than the other

We have upgraded both of pelletising plants with high efficiency scrubbers

We made improvements in the bottom layer of our screening system on the sintering valve to ensure grain size control and achieved dust emissions reductions. Before doing this the sinter plant was one of the main sources of dust in the plant

R: What was the reason for the implementations?

FP2-SS: The carbon tax was the major driver for reducing carbon emissions. When those things started it was a big thing in the industry and there was a lot of RND.

I think it was around 2010 when electricity outages started occurring and that was a major driver in those days for reducing electricity consumption and cogeneration. There are different technology options in cogen however I did not research those because we did not execute those. So that is something that happened before I got here.

Slag from ferrochrome manufacturing is sometimes processed further to recover chrome. It is crushed the sent to a flotation station and jigging plant. In the crusher units we have dust suppression sprayers

R: When was the implementation and is it still in practise?

FP2-SS: Plans for the implementation were in place however plans were not executed.

R: What was the effect or efficiency of the implementation?

*Answered from above.

R: What was the effect or efficiency of the implementation?

R: Which operations have implemented these new technologies or change in operations?

FP2-SS: FP2 only has a mining complex and the processing site where we have our furnaces. So, we are not a very big company.

R: Do you think ecoefficiency is improving in the industry?

FP2-SS: In my opinion eco-efficiencies always come with production efficiency benefits. If you are able to come up with an improvement in efficiency these will result in better in maintenance and productivity. For instance, less dust in the in the air will result in less expenses towards maintenance, it improves safety through better visibility and improved health and consequently enhanced productivity. In addition, the community will have a better opinion resulting from less dust complaints. Going forward, this aids towards better engagement with future projects requiring community support such as EIA's.

The ferrochrome industry is very aware of its social corporates responsibility. A lot of information is shared on the ferrochrome producer's association responding to legislation, reporting, initiatives and how to influence market where possible. With regards to safety and the environment, FAPA has been involved extensively in that field.

R: Any Additional comments.

NO additional comments.

B.6.3 FP2-WM

Name: FP2-WM

Organisation: FP2

Date: 23 August 2018

Time: 16h00 – 17h00

Type of interview: Telephonic interview. Could not record interview and therefore could not transcribe word for word.

FP2-WM's commentary on preliminary results.

Ore used: Ore consumption is in the same range as the company consumption however the company consumption rate is higher.

Mineral waste: Although uncertain, industry performance does show similar trends. Uncertainty brought about by uncertainty in of what has been included in the mineral waste accounting of preliminary results.

Water: Company water consumption is a bit lower than reported results especially in the last three months from the time of this interview however it is within the range.

Electricity: Electricity consumption is a function of:

- Ferrochrome production recipe – Ferrochrome is varied and therefore the specifications of the final product influence the energy requirements;
- Ore grade or quality – over 10 years ago lumpy ore was more available than present. Consequently, there is more;
- Fraction of slag produced as a result of gangue.

Chromite pellets are 10 - 15 mm pellets produced on site from concentrated chrome and reductant through a process of pelletising and sintering. The use of pellets in the industry and in the company has become common on account scarce availability of lumpy ore with required concentration levels. The higher the concentration of gangue in the smelter raw material feed the greater the energy requirement to produce a unit of ferrochrome. The company can only produce enough pellets to run the plant at 77% capacity.

Emissions (CO_2, SO_x, NO_x and particulates): The emissions seem to be representative of industry performance but cannot confirm without data present.

It is worth noting that in 2009 the company closed it's open furnaces to closed furnaces. Open furnaces are vessels with no fixed roof structures and therefore the process material is open to the atmosphere. Air dilutes the oxygen and thus leads to higher electricity consumption.

Closed furnaces on the other hand have a closed roof structure. NOx is removed in a scrubber Air does not feature significantly with the raw materials. In addition, gas fumes from smelting are captured and not released to the atmosphere without being treated or being incinerated.

SOx emissions: The choice of reductant affects emissions. Anthracite which has a higher FeS_2 content than coke produces higher SOx emissions. However, anthracite is cheaper than coke, therefore anthracite is more commonly used in the industry.

Carbon monoxide from the smelter leaves the furnaces at high temperatures. Heat energy from the hot CO stream is used to for sintering of pellets thus reducing energy requirements and emissions. This is common practice in the industry. During start up and shut down for units preceding and after the sintering plant, propane is used as a fuel.

NOx: There is no specific driver for NOx.

R: What is your current position and experience?

FP2-WM: Works manager – overseeing production, beneficiation, furnaces (smelting), sintering, plant tails, internal…

FP2-WM: To your knowledge has there been any new technology or change in operation that has been implemented leading to a change in emissions, output and input of operations regarding ferrochrome production since 2008?

FP2-WM:

- In 2009 two open furnaces were converted to closed furnaces.
- Increase pellet load from 60% to 90% between 2016 and 2017 into furnaces.

R: What was the reason for the implementation?

FP2-WM:

- To continue being competitive in challenging market conditions
- To reduce costs
- The need to remain legally compliant

R: Is there any pressure regarding environmental stewardship and emissions from the market?

FP2-WM: With regards to environmental expectations in the market, China and Europe constitute majority of ferrochrome consumption and do not penalise significantly.

R: When was the implementation and is it still in practice

FP2-WM: [Implementation dates have been given above]. The implementations are still in practise.

R: What is the effect or efficiency of this implementation?

FP2-WM: The implementation led to a reduction in energy requirements and reduced emissions from the smelter.

R: Which operations have implemented this new technology?

FP2-WM: FP2 has smelting and pelletising operations are situated in [the operating town]. On account of the implementations focusing on the smelting and pelletising, it follows that the implementations are at the [operating town] plant.

R: Do you think eco-efficiency is improving in the industry?

FP2-WM: Yes because of legal compliance requirements, cost reduction benefits and reduction of emissions.

R: Additional comments

FP2-WM: Resource management is increasingly becoming more important and cannot be ignored if a company is to be competitive.

B.6.4 CF1-Dir

5.1 Meta data

Name: CF1-Dir

Organisation: CF1

Position: Director

Date: 07 September 2018

Time: 07h30 – 09h30

Type of interview: Live interview

Commentary on preliminary results

R: Thank you so much for meeting with me. I would like to start off with a few graphs of Glencore Merafe's graphs and would like to get your opinion on how far they represent the industry.

CF1-Dir: Glencore?

R: Yes, because they are the only ones that publicly show they're results.

CF1-Dir: So that is project Lion and things like that?

R: So, this is for the entire operation.

CF1-Dir: There is something important here that we need to talk about. What is ferrochrome? Because there [are] different products that they sell as ferrochrome.

R: It is not distinguished what the product is. They don't say which product is charged chrome, low carbon and high carbon.

CF1-Dir: That is my point. They vary significantly on how you make this stuff. So want to use ferrochrome as an aggregate?

R: It would be nice to know what that information is but they do not reveal sort of information to the public.

CF1-Dir: Ok. There's a couple of things there that might influence your graph. The first thing is that ferrochrome is cyclic industry. It goes through phases of boom and bust. When the prices are high everybody builds up capacity and when the price drop everybody shuts everything down. That cycle is about three to five years long. That will impact significantly on the electricity consumption, the emissions are going to be the same. This graph that shows production shows a decline probably because of the cycle. If you the energy production trend is for that ferrochrome production, then it probably normalised and make sure it is the right units.

If you look at production in 2009, the production is way down, if you at electricity consumption in 2009 it is about the same throughout. If you at energy consumption in 2009 it is about the same. If you look at electricity consumption and production, those two correlates, whereas if you look at energy, it remains the same. So, the question is what is energy?

R: Indirect energy would be defined as energy from the grid that is not produced in house. On the other hand, direct energy is energy would from power produced internally.

CF1-Dir: Then the indirect energy trends should correlate with the electricity consumption figures. So, the first question that should be answered should be what is this energy? I have got an idea if this is the lion project. What the guys are looking at there was either preheating or pre-reduction

[Diagram drawn by interviewee for illustration]

With [a] ferrochrome production black box you have input and outputs but what I do not see from you is energy flaring which is a significant by product in form the of carbon monoxide. Carbon monoxide is a combustible by product. If you pass by any ferrochrome furnace you will see that there is a huge flair that burns which could be as much as 20% of energy consumption. What a lot of the guys are beginning to do is that you will have about 100 units of electricity consumption, then you will have 20 units of energy flaring out in the form of heat energy or chemical energy. What they are starting to do now is, instead of releasing that potential energy into the atmosphere, they are starting to use that energy inside the black box. This is done through a couple of methods

Preheating – Some of the inputs in there furnace are raw materials coming in a big conveyer belt. The heat is then used to heat up the raw materials coming in because it goes in like a big furnace which is like an oversized welding machine. You have all sort of raw material like coal as part of their recipe. As that heat is used to heat up raw materials, the electricity consumptions then reduces.

Pre-reduction – This is particularly difficult thing to do. A lot of ferrochrome people have looked at that not too many have managed to get it right. Samancor Chrome looked at that the dropped that. Exxaro also, although processing mineral sands and the process being similar to ferrochrome production, attempted pre-reduction but they could not get it right.

Cogeneration – This is essentially electricity from waste. The same thing that burns there you can burn inside an internal combustion machine. The energy quality from that is low with calorimetric values of about 10 to 11 MJ/m3 of that gas fumes. It's not something that can be used into any mechanism to produce electricity such as turbine. The smallest turbine that can be used for this waste is about 25 MJ. The biggest one is at Hernic which is about 75 Mw. I am not familiar with Glencore ones. You should note that once cogeneration is in practice then the reduces the 20% value mentioned. In addition, because CO gas is poisonous, they still flair that for safety reasons.

R: With regards to preheating, is the gas combusted or energy used as heat energy?

CF1-Dir: Think about it like a welding machine. Think about it as a batch process, with a roof. You fill it up with raw materials and you apply waste gas from the furnace into it. So, the raw materials come in at ambient temperatures and once the hot waste gas is introduced the temperature of the raw materials will increase.

R: Is the waste gas treated before it is mixed with the raw materials?

CF1-Dir: No, it is not changed. It is different from the cogeneration where particulates are removed, moisture is reduced and cv values are maintained to have constant feed into the engine.

R: I am not sure if you are familiar with sintering for pellets. Is the heat energy from the hot furnace exhaust gas used to heat up the pellets or is the hot gas treated or combusted to heat the pellets?

CF1-Dir: So, preheating is one use of the gas. So, they take a certain portion of that gas for preheating, some for sintering, some might be sent for cogeneration and some is whilst some is flared. Also note that the more you gas that is flared the less efficient the plant runs because it affects the energy put into the plant whilst reducing the waste. I am not certain however electricity constitutes about 30- 50% of operating costs. There for if your costs are down the price can be lowered to be more competitive in the world market. In the past, around the early 2000s South Africa was the price maker because South Africa use to provide bulk of the ferrochrome. At some point platinum producer realised that part of the platinum ore produced contains a lot of chromium and therefore decided to sell it to international markets without adding value to it. The moment other people started more ferrochrome, South Africa lost market share dominance and could no longer influence the price as before.

R: I think it was in 2012 when South Africa lost dominant market share.

CF1-Dir: That sounds about right. See there are a couple of things that you must consider, one being that the price of electricity was very cheap. Ferrochrome production plants are incredibly energy intensive. Plants today will be designed as efficiently as possible. In the 70s and 80s the was not real intensive to be efficient because electricity was cheap and did not significantly affect profitably.

The other thing that has changed significantly roughly around the same period is the awareness of climate change and greenhouse gases. As you know CO when released into the atmosphere gets converted into green CO2 same as greenhouse gases. There are a number of drivers that are making the producers reduce CO. I am speaking too much now is there anything else that you would like to know?

R: Basically, we are on the right track because the first part of the project was trying to establish whether the trends that I have showed is a reflection of what is happening on the ground with regards to the industry. In addition, trying to figure out what the cause and effect of some of the innovations that have developed are in the industry. I also have a couple of questions here to further direct the interview.

CF1-Dir: Ore consumption is in the same range as the company consumption however the company consumption rate is higher.

Mineral waste: Although uncertain, industry performance does show similar trends. Uncertainty brought about by uncertainty in of what has been included in the mineral waste accounting of preliminary results.

Water: Company water consumption is a bit lower than reported results especially in the last three months from the time of this interview however it is within the range.

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- Fraction of slag produced as a result of gangue;

Chromite pellets are 10 - 15 mm pellets produced on site from concentrated chrome and reductant through a process of pelletising and sintering. The use of pellets in the industry and in the company has become common on account scarce availability of lumpy ore with required concentration levels. The higher the concentration of gangue in the smelter raw material feed the greater the energy requirement to produce a unit of ferrochrome. The company can only produce enough pellets to run the plant at 77% capacity.

Emissions (CO_2, SO_x, NO_x and particulates): The emissions seem to be representative of industry performance but cannot confirm without data present.

R: What is your current position and experience?

CF1-Dir: When you talk about the ferrochrome industry and ilmenite industry, some of the player in the industry have been my clients at some point in time. We are in the energy space and nowhere else. The intent of the work that we have done for them was about energy, either cogeneration or production of energy or reducing carbon footprint. This includes Merafe (Xstrata) Samancor ferrochrome), Exxaro African Rainbow. At that point in time it was called Tronox it was an ilmenite plant. We built that plant.

R: I just want to make sure that I represent you well. Would I be correct in saying that you were a consultant that was involved in all the projects that you have mentioned?

CF1-Dir: We not only consulted but also were involved in implementation and construction of the projects. If you go a little further south, you will see that there is a plant in Saldana bay.

R: To your knowledge has there been any new technology or change in operation that has been implemented leading to a change in emissions, output and input of operations regarding ferrochrome production since 2008?

CF1-Dir: It is the same stuff that I have mentioned to you. It is about using the waste gas for cogeneration and preheating mostly. The certainly are other uses of it other than the ones have mentioned. Even the electrodes that are used in the furnaces are being investigated to reduce power production. You would need to talk to operational managers to tell you those kinds of projects.

R: What was the reason for the implementation?

CF1-Dir:

- The economic rationale to reduce the pre unit cost
- To whole climate change thing is important to these guys from a moral perspective because they are big emitters
- The looming carbon tax has also been a driver although it has been debated around for a quite a number of years now. The government has been talking about introducing the tax whilst the industry has responded that the tax would make business more difficult. The electricity price is already an incentive.

R: Is there any pressure regarding environmental stewardship and emissions from the market?

CF1-Dir: With regards to environmental expectations in the market, China and Europe constitute majority of ferrochrome consumption and do not penalise significantly.

R: When was the implementation and is it still in practice**?**

CF1-Dir: I can’t say for sure because the cycles will usually determine whether the projects can be justified. As early as the year 2000, the industry was already doing projects.

R: From looking online I have noticed that you have been involved in a number of projects around 2009 to 2012 but have not been involved since that time. I did not realise that work done as early as the year 2000.

CF1-Dir: In the early 2000s the big driver was the introduction of carbon credits. This was a certified emission reduction. For every unit of carbon that you could produce that has been avoided you would be awarded a carbon credit. The European Union had an arrangement such that if you reduced your carbon emission and you could prove that it would not have happened without your project then they company would get paid for that subject to set conditions.

Another dimension was that one could be rewarded for an implementation that one was expected to do. These credits could be sold into the open market. The price evolved around the market that developed at the time starting at round 6 euros for every ton of CO2 and this made a big difference with the justifying the projects. Around 2005 the price of started to decrease until it became worthless. That for while motivated the industry to be energy efficient.

R: What is the effect or efficiency of this implementation? You have talked about how cogeneration results in the reduction of energy supplied to the smelter.

CF1-Dir: It has led to the reduction of energy supplied per unit ferrochrome.

R: Which operations have implemented this new technology?

CF1-Dir: They have all done. For instance, Samancor chrome has done feasibility studies. You spend 30 million rand in the process and then the price of carbon credits crashed, and we decided to stop the project. So, it is not implemented we just did the feasibility studies. Something similar happened at Hernic, Government was going to buy electricity for cogeneration but then government retracted.

R: Just to confirm, there are a number of projects with EIAs, from what you have said would that mean that not all of them have been implemented?

These things do not happen in a vacuum. Sometimes the market requires that you drop the price of certain inputs and you need the government to help you with that. If the government withdraws the commitment, then the project will stop. Take a look at the IRP for instance which has changed over the past. In particular Ministerial determination. During the era of Ben Martin who determined that the country need a cogeneration power, the industry prepared to sell power to government by developing projects like. However, as the Zuma era, nuclear energy was heavily supported and thus caused the plans to buy cogeneration to stop. Government instability deters such project as they require a lot of money and time.

African Rainbow had a ferrochrome smelter which they eventually closed down and moved to Papua New Guinea, I am not certain exactly where but the instability is causing ferrochrome industry to decline.

R: Do you think eco-efficiency is improving in the industry?

CF1-Dir: Yes, I do because they price takers and they have to do everything they can to reduce costs. The costs of mining (digging) is not getting cheaper plus labour is getting more expensive and electricity is becoming more expensive.

R: Additional comments

CF1-Dir: Not really.

B.6.5 CF2-Dir

Name: CF2-Dir

Organisation: CF2

Position: Director

Date: 09 October 2018

Time: 14h30

Type of interview: Live interview

Commentary on Trends

R: I would like us to go through a couple of reports just to see if they are representative of the industry. Only Glencore-Merafe publishes their reports.

CF2-Dir: Primarily Glencore, Hernic and Samancor.

R: Unfortunately, only Glencore and IFML publishes their results.

CF2-Dir: That should be good for you

R: I was hoping you could have a glimpse at the trends and see whether…

CF2-Dir: I am not familiar with the process.

R: Perhaps maybe the mineral waste?

CF2-Dir: At some stage we worked on a report regarding Cr (VI) and I cannot remember the outcome of that, but I do not think it was much of a concern.

R: I was hoping to get your opinion on slag with fluctuates haphazardly whilst production is increasing. Would you have an idea of what causes that.

CF2-Dir: There are several barriers to the use of the slag because it is currently classified as pre hazardous waste irrespective. Ferrochrome slag only becomes a hazard if it is ground up. You will get that from any inorganic material. In as far as leaching characteristics, it is inert. The major limitations in as far as using that is that the department of environmental affairs regards it as a hazardous waste. If you want to use it then it is an onerous process. Most companies, because of the definition of hazardous waste do not want to put it on the market. Even if you give it away to build a road in a township, if a person gets a hold of that information, then the company will be regarded as dumping hazardous waste on the people. The department is taking notice of that and there is some work being done but it is far from being used.

R: Would you say that influences the production of slag, the manner in which slag is stored?

CF2-Dir: Not the production. That depends on the market of the product, but the accumulation is affected by legislation. The definition does not only affect regulations, but it is also a matter of perception. If people have to choose between using it as an aggregate concrete in comparison to dolomite, auxite and all those virgin materials, they will take those virgin materials because there is always the fear that it is hazardous. So, there is a kind of a market resistance against which has nothing to do with the quality of the material.

R: Do you think that aspect of the industry affects the process upstream?

CF2-Dir: Not that I am aware of. There is nothing that they need to do to make it less hazardous for the end use. There are two factors that have to be considered.

There one factor is that if you want to manufacture something like concrete and tiles, there are multiple possible uses of that. You have to assess whether it is fit for purpose by doing the physical tests to ensure that it is durable.

The other aspect is to confirm whether it is safe to use with as far as matters of leaching and ground water contamination and other similar aspects. This aspect has been tested. Other countries in Europe is used in road and building construction. There was a case where Outokumpu in a Scandinavian country where the company was using the material as building material. The local environmental authority files a case against the company and the ruling was in favour of the company.

R: As far as the preliminary results are concerned, would you say that the results from Glencore are representative of the industry?

CF2-Dir: I would say they are with environmental part that I am familiar with. We have done classifications with them in accordance with Global Health Association GHS. There's a South Africa association SAMS 1234 and they have done waste classifications in terms of their streams.

R: What is your current position and experience?

CF2-Dir: As far as this is study is concerned, it is the assessment of ferrochrome waste in terms of potential environmental and health risk.

R: To your knowledge has there been any new technology or change in operation that has been implemented leading to a change in emissions, output and input of operations regarding ferrochrome production since 2008?

CF2-Dir: know we had a request from one of their smelters to do a classification for them 5 years ago. I would not think that the process has not changed that might be because most of the smelters are not new. The newest on is the lion smelter in Steelpoort. As far as I know it is old technology which has been well established.

R: What was the reason for the implementation?

CF2-Dir:

- It was probably market driven. There was a good market for the product and raw materials, and they had the raw materials.

R: Is there any pressure regarding environmental stewardship and emissions from the market?

CF2-Dir:

- With regards to environmental expectations in the market, China and Europe constitute majority of ferrochrome consumption and do not penalise significantly.
- Some have industries have modified their processes so that their waste can be used further. That is referred to as valorisation and is very active in Europe. So the concept is centred around modifying the process such that the waste can be utilised.

R: When was the implementation and is it still in practice?

CF2-Dir: As far as I know it is still in production.

R: What is the effect or efficiency of this implementation? You have talked about how cogeneration results in the reduction of energy supplied to the smelter.

CF2-Dir: I do not know.

R: Which operations have implemented this new technology?

CF2-Dir: I as far as I am aware Glencore is the only one that introduced a new smelter.

R: Do you think eco-efficiency is improving in the industry?

CF2-Dir: In terms of emissions yes. There is a lot of regulatory involvement in motivating the mining. I would say regulations are the only reason why companies would reduce emission. Some of these regulations are really tight particularly with particulate emission which are difficult to manage.

R: Additional comments?

CF2-Dir: My view is that we are really missing an opportunity in this country by almost obstructing the use of these materials because of a peculiar definition of whether it is hazardous waste or not. It can be used and there are so many advantages in that use in avoiding greenhouse gases by using less virgin material. In some instance, the material is of superior quality for civil engineering and manufacturing processes. I think there should be a lot more drive in using the material for multiple purposes.

We are still digging holes in the ground to unearth virgin material.