Improving by-product gas utilisation in steel milling operations

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Thesis accepted in fulfilment of the requirements for the degree *Doctor of Philosophy in Mechanical Engineering* at the North-West University

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Graduation: July 2020

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ABSTRACT

Title: Improving by-product gas utilisation in steel milling operations

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Degree: PhD Mechanical Engineering

Keywords: By-product gases, coke oven gas, calorific value, reheating furnaces, combustion improvement, air-fuel ratio.

Iron and steel manufacturing are energy-intensive processes. Rising energy and operational costs have placed South African steel manufacturers under financial strain, while they struggle to remain afloat within an extremely competitive global market. Declining production and export figures, as well as increasing imports, have adversely affected the sustainability and profitability of the local market. It is, therefore, imperative for local manufacturers to implement operational change strategies without additional capital investment requirements in order to save energy and reduce costs.

Hot-rolling processes of steel milling operations use reheating furnaces to elevate the temperature of the steel to a state of plastic deformation prior to rolling. The reheating furnaces combust fuel gases such as by-product gases or natural gas for thermal energy. They consume 70 % of the energy of the hot-rolling processes. By-product gases are combustible carriers of energy. Coke oven gas (COG) carries 18 % of the energy input of the coke production process. The energy content of COG was found to be competitive with natural gas and compatible for high-energy requirement applications, such as in reheating furnaces.

The challenge arises in that the calorific value (CV) of COG fluctuates over time. These fluctuations prove problematic during the control of COG combustion processes as the air-fuel ratio needs to be adjusted accordingly. Furnace operators typically rely on a trial-and-error method for air-fuel ratio adjustments in response to the fluctuating calorific value of coke oven gas (CV of COG). This causes furnace temperature instabilities, energy inefficiencies and production losses. Additionally, COG has a high impurity content inherent from the coal. These impurities clog CV of COG analysing equipment.

Several alternative tools are available to estimate the unavailable CV of COG; however, these tools do not account for the fluctuating nature of COG and only provide static estimated values. Based on these challenges, a need was identified to facilitate more stable operations of the furnace. The aim of this study entails the development of a new methodology to adjust the air-fuel ratio according to the incoming CV of COG and the current furnace operating conditions. The historic behaviour of the furnace is used in the control strategy.

To address the recurring events where CV of COG data is unavailable, a novel methodology is developed for a time-continuous estimation of CV of COG for stable process applications. A seven-step methodology was developed whereby an appropriate method can be selected for the determination of CV of COG, based on the available data and measuring equipment. Three methods are presented, with varying accuracy and consistency.

Pilot studies were undertaken on a billet mill reheating furnace in order to validate the air-fuel ratio adjustment methodology. The results verified that the air-fuel adjustments were within 94 % - 98 % accurate, resulting in a significant improvement in temperature stability. A reduction of 0,9 GJ/t in the energy intensity was determined. Based on the average natural gas maximum price of R 141/GJ, an annual potential cost saving of approximately R 7,5 million on natural gas purchases can be realised.

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ACKNOWLEDGEMENTS

The completion of this thesis is such a surreal experience. It is a product of collective efforts, inputs and prayers from people whose lasting and immeasurable impact I cannot begin to fathom.

In that regard, I would like to express my sincerest gratitude to the following:

- To God, my Almighty Father, to You be the praise, honour and glory. Everything that I do and have comes from You. Ke a leboga Mmopi!
    - *"I can do all things through Christ who strengthens me" (Philippians 4:13).*
- To my parents (Morwamakoti and Matseke Mampuru) and siblings (Nkgabe, Diphale, Matime and Segatle Mampuru), thank you for your patience and allowing me to further my studies. I am eternally grateful.
- To my fiancé Thabiso Moropa, you reminded me the power of prayer throughout this journey. For your consistent support, love and motivation, I will remain eternally grateful.
- ETA Operations (Pty) Ltd, TEMM International (Pty) Ltd and Enermanage (Pty) Ltd, thank you for the financial support.
- Prof. E.H. Mathews and Prof. M. Kleingeld, I appreciate the opportunity to do my doctoral studies at CRCED Pretoria.
- Prof. M. Kleingeld, thank you for your guidance as my study leader.
- Dr J. van Laar, thank you for your academic mentorship and inputs during the write-up on this thesis.
- Dr J.H. Marais, Dr S.G.J. van Niekerk and Dr W.A. Pelser, thank you for your inputs and feedback during the progress on this thesis, much appreciated. To J.J. Swanepoel, thank you for your assistance with the reheating furnace tests.

ABBREVIATIONS

AMSA	ArcelorMittal South Africa
BFG	Blast furnace gas
BF-BOF	Blast furnace – basic oxygen furnace
BOF	Basic oxygen furnace
BOFG	Basic oxygen furnace gas
CER	Certified emission reductions
CO_2e	Carbon dioxide equivalent
COG	Coke oven gas
CV	Calorific value
DoE	Department of Energy
DRI	Direct reduced iron
EAF	Electric arc furnace
EU	European Union
GST	Goods and service tax
ISO	International Organisation for Standardisation
MPC	Model predictive control
Nersa	National Energy Regulator of South Africa
OECD	Organisation for Economic Co-operation and Development
OSPP	On-site power plant
PCI	Pulverised Coke Injection
PI	Proportional-integral
SDS	Sustainable development scenario
U.S.	United States
WI	Wobbe Index

CHEMICAL REAGENTS

CO	Carbon monoxide
CO_2	Carbon dioxide
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Isobutane
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
NH_3	Ammonia
N_2	Nitrogen
NOx	Nitrous oxide
O_2	Oxygen

UNITS OF MEASUREMENT

atm	Atmospheric pressure
°C	Degree Celsius
EJ	Exajoule
GJ	Gigajoule
GJ/t	Gigajoule per tonne
hr	hour
MJ/Nm^3	Megajoule per nominal cubic meter
Mt	Million tonnes (metric ton)
MW	Megawatt

MWh	Megawatt hour
PJ	Petajoule
R	Rand (South African)
R/GJ	Rand per gigajoule
t	Tonne (metric ton)
t/hr	Tonne (metric ton) per hour
US$	United States Dollar

1 INTRODUCTION

Iron-making blast furnace [1]

[1] World Steel Association [BE], [Online] Available: steeluniversity.org. Accessed: 2019-10-10

1.1 Background

1.1.1 Preamble

An overview of the existing state of the global and local iron and steel manufacturing industry will be given. An analysis of the primary energy sources, their applications and associated costs in integrated steel operations will be given. This will be followed by a discussion of the environmental, social and economic impacts of the industry.

By-product gases[2] and their utilisation as potential alternative energy sources will be introduced and discussed. A critical literature review on the existing applications, management and developed solutions for by-product gases utilisation will be conducted. The outcomes will be used to identify the shortcomings of the existing solutions. From this, the need for this study and the novel contributions will be formulated. Details of the thesis layout and a chapter summary will conclude.

1.1.2 The global steel market overview

There has been a significant rise in global steel mass output in recent years. Global steel production has increased by more than 110 % overall between 2000 and 2018. Mass production figures have escalated from 850 million tonnes (Mt) in 2000 to 1 808 Mt in 2018 [1]. The world steel manufacturing market has seen drastic changes in production in recent years. The world crude steel production figures are shown in Figure 1.

The early 2000s have particularly seen a significant change in steel production trends. Prior to the year 2000, steel output had averaged an overall growth of 10,2 % over 20 years. A significant decline in production was experienced globally in 1998 due to the Asian financial shock. The Chinese steel production boom since the year 2000 has significantly shaped the global iron and steel markets[3]. Thereafter, the annual global production has more than doubled in capacity in less than 20 years.

[2] In the context of this thesis, by-product gases, flue gases and off-gases have synonymous meanings.
[3] Mining Technology, “Chinese steel policy shifts to flatten out the iron ore boom by 2022,” Mining Technology, 28 September 2018, [Online] Available: mining-technology.com. [Accessed: 2019-01-10].

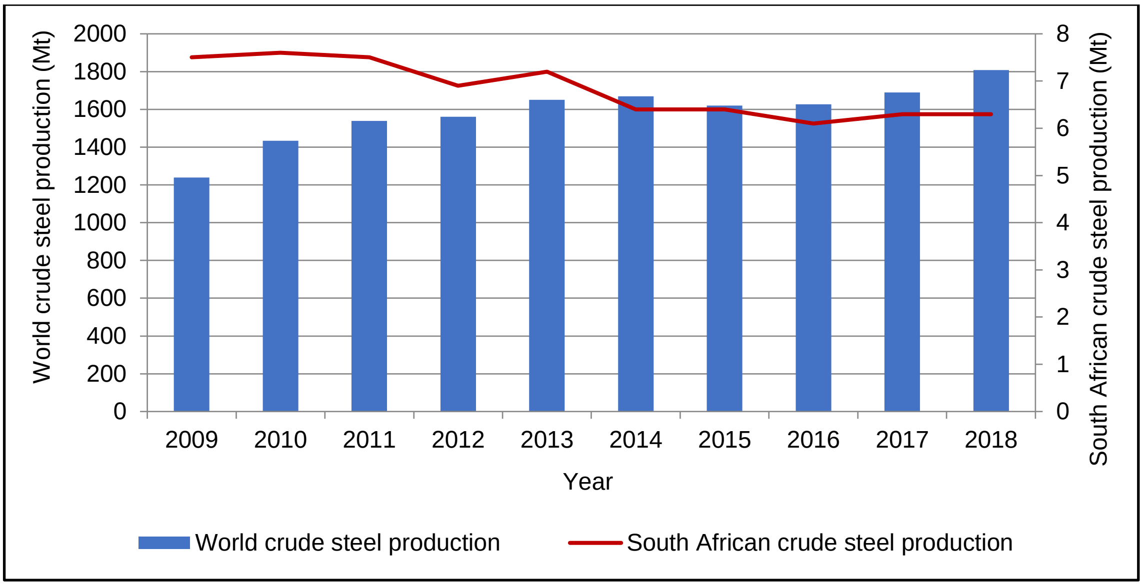

Figure 1: World vs South African crude steel production, 2009 – 2018[4]. Adapted from [1]–[3]

The 2000s steel production boom has since tilted the scales on steel demand and supply. Steel supply outweighed its demand, resulting in a steel excess. This caused imbalances in product flow within the market. A state of product overcapacity within the steel market was experienced and still prevails [4]. Popescu *et al.* [5] suggested that the key driver for global steel overcapacity is the continued investment of resources by powerful local governments in order to increase production, without much regard for market fundamentals [5].

The global steel demand and production has dominantly been driven and influenced by China [6] [5]. The contribution by steel production input into the global market by major producing regions is presented in Figure 2. As can be seen, China alone was responsible for 51 % of the global crude steel production in 2018. This is an increase of 2 % from 2017 [2]. There is an overall net positive outlook on the growth of the global steel manufacturing industry. However, this growth remains exclusive of emerging steel markets, which otherwise experience decelerating growth [7].

[4] Organisation for Economic Co-operation and Development (OECD), “Steelmaking capacity.” [Online]. Available: stats.oecd.org. [Accessed: 2019-01-10].
[5] Tasneem Bulbulia, “Global steel production, consumption growth to slow – Fitch,” Creamer Media Engineering News, 18 September 2018. [Online]. Available: engineeringnews.co.za. [Accessed: 2019-01-09].

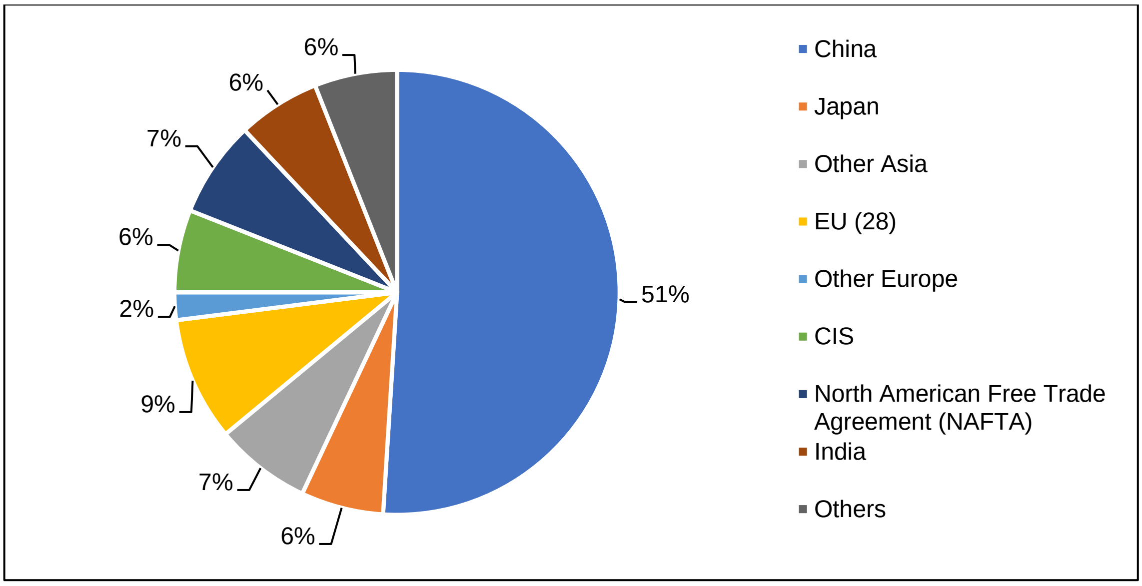

Figure 2: World crude steel production input distribution in 2018. Adapted from [1]

1.1.3 The South African steel sector

South Africa has received rankings for the 24th and 25th places among major steel producing countries in 2016 and 2017, respectively. A combined total of 6,1 and 6,3 Mt of crude steel was produced during the respective years [2]. The ranking and production figures have remained unchanged in 2018 [1]. The local steel mass production trend between 2009 and 2018 is also portrayed in Figure 1. Steel production figures in the local and global markets are portraying opposite growth trends in the last 10 years.

The local steel sector has seen a 4,5 % year-on-year decline in production in 2015/16. This stemmed from high production costs and a decline in demand and trade of locally manufactured steel [6]. The global steel product surplus is a contributing factor to the struggling local market. The South African steel manufacturing sector has, as a result, experienced a decline in profitability [6].

Plummeting production figures have stayed the course for the local steel sector. Figure 1 shows a progressive decrease in steel production over the recent 10 years. A decline in production by 16 %, from a high of 7,5 Mt in 2009 down to 6,3 Mt in 2018, was seen. This is an indication that local steel manufacturers are struggling to remain afloat amid the prevailing economic and financial strain [4].

According to Dondofema *et al.* [8], the alarming decline in production may be an indication of an approaching extinction of the local sector [8]. They predicted that if the deteriorating state does not stop and reverse, the local steel sector risks reaching the end of its existence within two decades as from the year 2017 [8]. The possible extinction is evident from the recent closure of major local steel producing corporations [9].

Cape Town Iron and Steel-works (Pty) Limited closed its doors and ceased its operations in 2009 [8]. However, a 29 May 2018 article from Engineering News has reported that the company has since re-opened its operations under new ownership [6]. ArcelorMittal South Africa (AMSA) operations in Vanderbijlpark and Vereeniging followed suit and closed their mini-mill plants in 2012 and 2015 respectively. EVRAZ Highveld Steel and Vanadium Corporation also stopped its operations in 2016 [8].

The increase in steel imports while exports decline, is another threat crippling the local market. The global steel surplus has triggered a decline in steel exports for non-Chinese producers, including South Africa. The impact on the local sector is aggravated by high fixed costs and capital intensity [10]. High quality, cheaper steel is gradually displacing the demand for locally produced merchandise. South African semi-finished and finished steel products exports and imports trends are shown in Figure 3.

Figure 3: Semi-finished and finished steel product exports and imports, 2008 – 2017. Taken from [3]

Figure 3 reveals an appreciable growth in exports by an average of 18 % between 2008 and 2010. This brief positive occurrence may be attributed to the global depression in 2008 that resulted in top producers slowing down on their output. A sharp decline in exports followed

[6] Kim Cloete, "Cape Town Iron and Steel Works officially opened", Creamer Media's Engineering News, 30 May 2018, [Online] Available: engineeringnews.co.za. [Accessed: 2019-01-16].

between 2010 and 2013. Over this period, steel exports decreased by 37 % from 3 Mt down to 1,9 Mt.

These trends are an aftermath of the closure of local steel enterprises, as discussed earlier. A further averaged incline in exports by 9 % over 4 years until 2017 was seen. Of concern is the persistent overall increase in steel imports into the local market, which increased by 50 % over 7 years since 2010. The historic trends for local imports and exports of semi-finished and finished steel products between 2008 and 2017 are compared in Figure 3.

1.1.4 Energy supply and cost for the South African steel sector

The iron and steel manufacturing industry is highly energy-intensive [11]–[13]. It is the largest consumer of energy in the manufacturing sector globally [14]. Due to rapid developments of this industry, its total energy consumption increased by more than 220 % between 1996 and 2012 [15].

The steel sector was accountable for 18 % of the total world industrial final energy consumption in 2013, amounting to 20 364 PJ[7] [13].The energy contribution for the South African steel sector is typically sourced from electricity, coal and natural gas [16]. The energy source distribution to local steel plants in 2015 is shown in Figure 4.

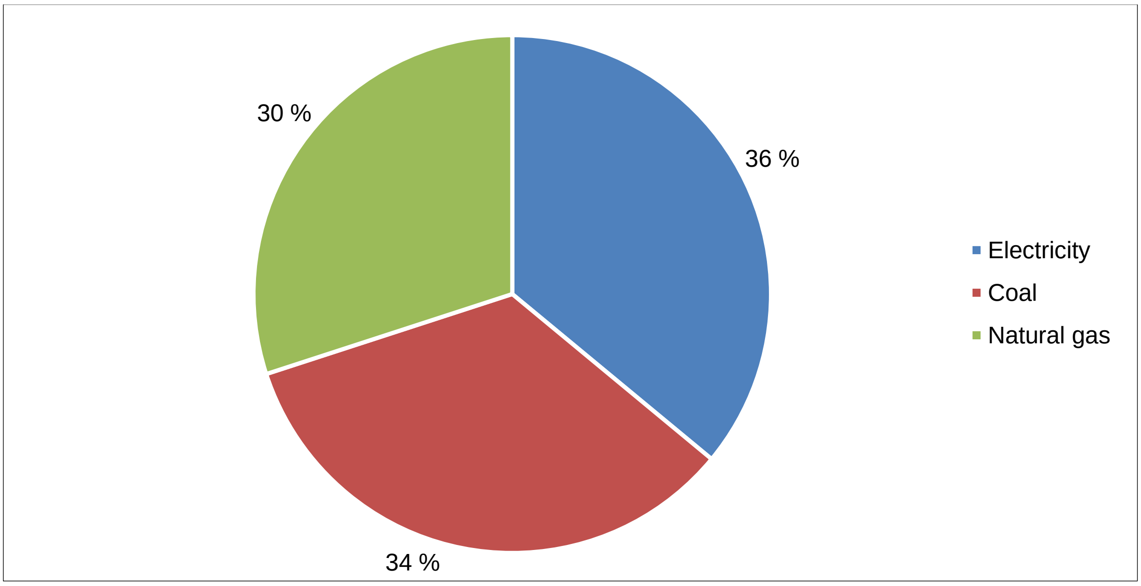

Figure 4: Energy demand in South African steel plants, 2015. Taken from [16]

[7] 1 Petajoule (PJ) = 1 x 10^{15} Joules (J)

Electricity

Electricity is an important and integrated commodity upon which the support of local industrial and economic systems depend. With an annual generation capacity of 240 300 GWh, Eskom is the largest supplier of electricity for South Africa. Coal-fired power stations generate 85 % of electricity at Eskom. This translates into a large carbon footprint by the local electricity supplier and dependent industries [6], [17]. With a demand of 36 %, electricity is a significant contributor to the production and operating costs of steel manufacturing facilities.

The increasing cost of electricity is one of the major challenges faced by South African steel manufacturers. Electricity prices have seen an increase of overall 290 % over 17 years since 2000 [18]. South Africa experienced an electricity crisis in 2008, after which the price increases went above inflation. The period between 2007 – 2015 has seen Eskom tariffs and inflation increase by approximately 300 % [6]. This increasing electricity cost trend is expected to continue in the long term [8].

By the end of 2018, the cost of electricity in South Africa was 12.5 % than in China [9]. In March 2019, Eskom requested electricity tariff increases by 17,1 %, 15,4 % and 15,5 % from the National Energy Regulator of South Africa (Nersa). The increases are for the financial years 2019/20, 2020/21 and 2021/22 respectively. Instead, increases by 9,4 %, 8,1 % and 5,2 % were respectively granted [10]. The consistently increasing costs associated with electrical energy will continue to exacerbate the financial strain on local steel producers.

Coal

Coal contributes 34 % to the energy needs of the local steel sector [16]. Secondary to thermal use, the largest demand for coal is for coke and PCI production for the blast furnace. Coal supply in South Africa is through production and imports. The local sector relies largely on imported coking coal [19].

The price of coal was at an average of $US 112/Mt in 2011. Thereafter, a decline in the price was seen until the end of 2015, reaching a low $US 57/Mt [19]. Coal prices have since recovered by 71 % from 2015, reaching a new high of $US 97,6/Mt in 2018. An average price

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[8] Luke Daniel, “Eskom to increase tariffs by 80% to recoup financial losses”, The South African, 02 August 2019. [Online] Available: thesouthafrican.com. [Accessed 2019-10-06]
[9] Businesstech, “South Africa’s petrol and electricity prices vs the world”, 24 March 2019. [Online] Available: businesstech.co.za [Accessed 2020-06-17]
[10] Tehillah Niselow and Lameez Omarjee, “Electricity prices to increase by 9.41%, says Nersa”, Fin24, 07 March 2019. [Online] Available: www.fin24.com. [Accessed 2019-03-07]

increase of 11 % was seen between 2008 and 2018 [20]. The increasing cost of coal aggravates energy costs for local steel manufacturers.

Natural gas

Natural gas contributed 30 % towards the energy input of local steel operations in 2015. The piped gas market in South Africa is dominated by Sasol. The Gas Act has exempted Sasol from regulated pricing since 2004. Thus, the price of gas varies over time for every customer. Prices are subjected to negotiations per customer according to Section 22 of the Gas Act [21].

Maximum selling prices are determined following the energy price indicator approach. Both assessment and regulation are performed by Nersa to provide a price “ceiling” [21]. The maximum pricing is affected by the prices of other energy sources, such as diesel, coal and electricity [22]. The historic trend for the maximum price of natural gas is shown in Figure 5. According to this figure, the maximum price of natural gas has increased by an average of 30 % between 2008 and 2017.

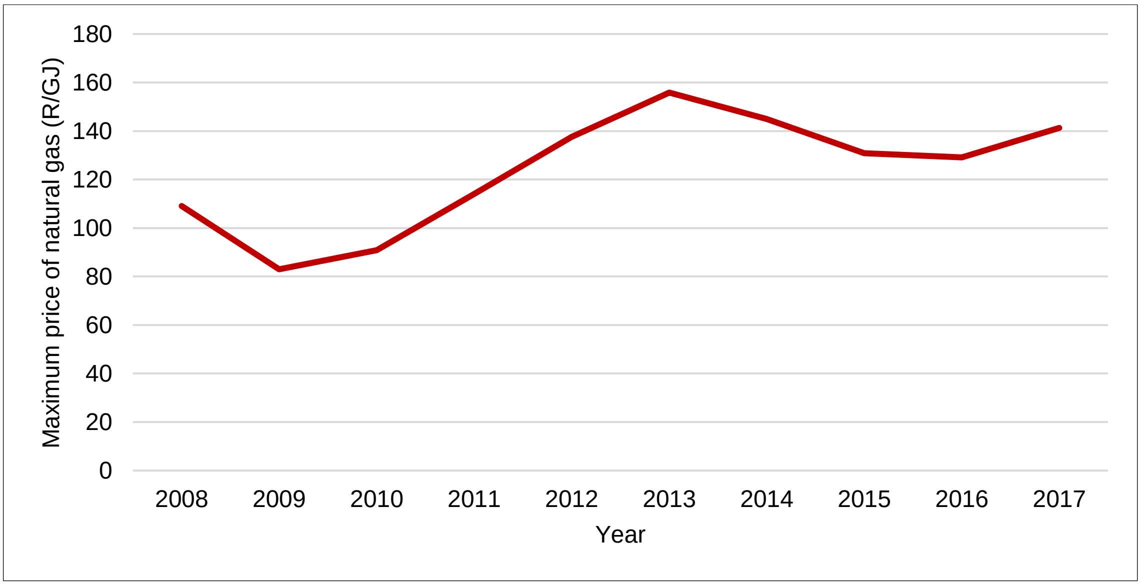

Figure 5: Historic trend for maximum price of natural gas. Adapted from [26], [27]

1.1.5 Environmental and social impacts of the steel industry

Carbon dioxide emissions

Energy efficiency improvement is important for the achievement of the three goals of energy policy – security supply, environmental protection and economic growth. In that regard, the environmental impacts of the steel industry cannot be ignored. The global manufacturing sector is accountable for nearly 36 % of carbon dioxide emissions. Of this, more than two-thirds is attributable to large primary materials industries [23], [24].

South Africa finds itself at the forefront of carbon dioxide emitters in Africa. This is due to its high dependency on coal as both a primary energy source and a production input source. To have an impact on environmental conservation, South Africa has committed to reduce greenhouse gas (GHG) emissions by 34 % and 42 % by 2020 and 2025, respectively [25]. The steel industry has a significant and direct impact on the state of the natural environment [14].

Carbon Tax

Carbon tax in South Africa has officially been implemented, effective as from 01 June 2019. Companies will be subjected to a phased in charge of R 120/t CO_2e of their GHG emissions, which will be accompanied by a 60 % - 95 % tax-free emissions allowances[11]. During the first phase of the implementation, i.e. between 01 June 2019 and 31 December 2022, the tax rate will be subjected to an increase by the amount of consumer price inflation plus 2 % for the preceding tax year.

During the second phase, i.e. 2023 – 2030, the tax rate will increase by the consumer price inflation amount for the preceding tax year. These increases will be determined by Statistics South Africa [39],[12]. The implementation of the carbon tax will increase the operational costs of affected industries [28], including the already strained iron and steel sector.

1.1.6 Conclusion

The background study highlights the challenges faced by the South African steel industry. Global steel production has been on the increase, while decreasing for the local sector. Imports and exports are increasing and decreasing, respectively. An increase in the cost of energy sources for the sector, i.e. electricity, coal and natural gas, has been shown. In order to remain competitive, it is imperative for local manufacturers to alleviate costs. This can be achieved by an increased and improved utilisation of available energy sources, such as by-product gases. This is discussed in the following section.

[11] South African Revenue Service, "Carbon Tax", SARS. [Online] Available: sars.gov.za [Accessed 2020-06-17]

[12] South African National Treasury, "Treasury tables carbon tax bill in parliament", South African Government, 21 November 2018. [Online] Available: www.gov.za [Accessed 2019-04-20]

1.2 By-product gases as energy sources

1.2.1 Overview of by-product gases

Iron and steel production in integrated facilities comprises of distinct, but interlinked and interdependent process stages. The main production stages include raw materials preparation, ironmaking and steelmaking. An overview of the iron and steel production stages is presented Figure 6. Details of the various production stages are given in Appendix A.

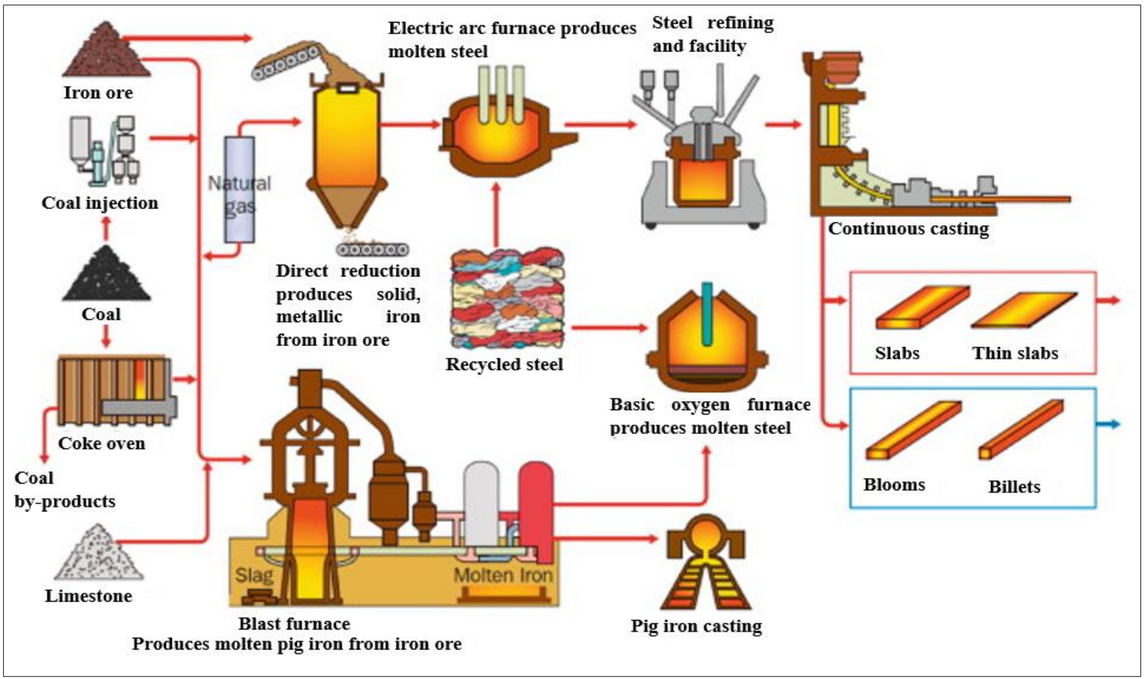

Figure 6: An overview of iron and steel manufacturing process stages. Taken from [29]

The various production stages produce by-products along with the desired products. These can be in the form of energy or materials. Of these, by-product gases are directly usable as energy sources. By-product gases are combustible carriers of energy with typical calorific values of 3 – 20 MJ/Nm^3 (at 25 °C, 1 atm) [13]. When efficiently managed and used, by-product gases can potentially contribute to 30 – 40 % of the energy consumption of steel enterprises [30], [31]. By-product gases produced in integrated steel operations include:

- Coke oven gas (COG);
- Basic oxygen furnace gas (BOFG); and
- Blast furnace gas (BFG).

[13] The calorific values reported in this thesis are normalised to 25 °C and 1.013 atm.

Coke oven gas (COG)

The carbonisation of coal into coke releases coke oven gas (COG) as a by-product [32]. The production rate is typically 300 – 360 m^3/t coke produced from 1,25 – 1,65 t of coal [33], [34]. COG has a relatively high energy potential [14] and it is the process gas with the highest calorific value (CV) within integrated steelworks [11].

COG accounts for 18 % of the energy output of a coke plant and it is characterised by a typical CV range between 17 – 20 MJ/Nm^3 [35]. This is almost half the CV of natural gas. The high energy content is due to its high concentrations of methane and hydrogen gases, with compositions of up to 27 % and 62 %, respectively [14], [32], [36].

Basic oxygen furnace gas (BOFG)

Molten iron undergoes decarburisation inside a basic oxygen furnace (BOF) [32]. During this process, the carbon contained within the molten iron is partially oxidised into carbon monoxide (CO). Basic oxygen furnace gas (BOFG) gets released from the BOF during this process.

The quality of BOFG is characterised by the concentration of CO [11]. Good quality BOFG has CO concentrations above 30 %. The energy content of BOFG is approximately a quarter of that of natural gas. It can be used to enrich other steelworks by-product gases [11]. BOGF is typically produced at a rate of 80 – 100 m^3/t molten iron produced [34].

Blast furnace gas (BFG)

Blast furnace gas (BFG) evolves from the blast furnace during the reduction of iron ore into molten iron. It is typically a mixture of CO, H_2, N_2 and CO_2, the typical compositions of which are shown in Table 1. Compared to COG, the energy content of BFG is significantly lower, with a CV ranging between 2,6 – 4,0 MJ/Nm^3. This is approximately a 10^{th} of the energy content of natural gas [11], [32], [37]. The typical production rate of BFG is approximately 1 400 – 1 800 m^3/t molten iron produced [34].

The use of BFG as a heat energy source is applicable with high process temperature requirement limitations. This is due to its low adiabatic flame temperature. As such, the use of BFG is limited to low-temperature processes. For higher temperature requirements, BFG is often enriched with natural gas or COG, to produce a mixed gas [11], [32].

Summary and discussion of by-product gases

Presented in Table 1 is a summary of the important properties of integrated steelworks by-product gases. Their properties are tabulated against and compared to those of natural gas. The CV range of COG, at 17 – 19,9 MJ/Nm^3 is highest among the by-product gases. Furthermore, it is secondary to that of natural gas, which ranges from 36 – 40,6 MJ/Nm^3.

Another critical observation from Table 1 is that natural and COG display similar combustion properties. The adiabatic flame temperatures (with dissociation, 500 °C air preheat, 10 % excess air) for natural gas and COG are close at 2 062 °C and 2 108 °C, respectively. At 1 000 °C products of combustion (POC) temperature, 500 °C air preheat and 10 % excess air, the available heat for COG and natural gas are 73,8 % and 73,3 % [38].

This close similarity of properties indicates that COG is as compatible for high energy and temperature requirement applications as natural gas. Hence, the combustion performance of COG and natural gas are expected to be similar [33]. The characteristics of COG make it more attractive for increased and improved applications in higher temperature requirement processes.

Table 1: Comparison of natural gas and steelworks by-product gases. Adapted from [13], [14], [33], [34], [38]

Fuel gas	Constituents	Composition (vol%)	Calorific value (at 25 °C, 1.013 atm) (MJ/Nm^3)	Adiabatic Flame Temperature (°C)	Available heat at 1 000 °C POC (%)	Typical production rate
Natural gas	CH_4 C_2H_4 N_2 C_3H_8 CO_2	~ 87 - 96 ~ 1,8 – 5,1 ~ 1,3 – 5,6 ~ 0,1 – 1,5 ~ 0,1 - 1	36 – 40,6	2 062	73,3	-
COG	H_2 CH_4 CO N_2 CO_2 Hydrocarbons	~ 55 - 60 ~ 23 - 27 ~ 5 - 8 ~ 3 - 6 < 2 Trace amounts	17 – 19,9	2 108	73,8	300 – 360 m^3/t coke produced

BOFG	CO CO_2 N_2 O_2 H_2	~ 60 - 70 ~ 15 - 20 ~ 10 - 20 ~ 2 ~ 1.5	5,8 - 8	1 974	67,4	80 - 100 m^3/t molten iron produced
BFG	N_2 CO CO_2 H_2	~ 50 - 60 ~ 20 - 25 ~ 20 - 25 < 5	2,6 – 4,0	1 383	3,6	1 400 – 1 800 m^3/t molten iron produced

1.2.2 Coke oven gas: An in-depth overview

Coke oven gas has seen a wide application as an industrial secondary energy fuel source. It is rated as a highly valuable by-product gas and there is a strong demand for its effective utilisation [39]. In integrated steelmaking facilities, COG can be used solely or as a mixture with other gases. It has been used as an energy source for reheating furnaces, blast furnace stoves, annealing lines, power plants and coke ovens.

Efforts to reduce coke consumption by blast furnaces in the past few decades imply that COG production has also been reduced. However, significant quantities of COG will still be produced because coke is an important constituent of the blast furnace charge. Improved utilisation of COG has received high interests for energy efficiency enhancement and GHG emission reductions [14].

Imbalances in COG production and consumption give rise to gas deficits and surpluses. In the case of a surplus, the gas is subjected to be flared. Currently, global by-product gas flaring practices culminate to exergy losses totalling to 1,7 EJ [14], i.e. 1,2 EJ of BFG, 0,4 EJ of COG and 0,1 EJ of BOFG [40]. Bermúdez *et al.* [14] did an overview study on alternative methods for valorising surpluses in COG supply. Hydrogen separation, methane enrichment and synthesis gas production were identified as the main and common methods [14].

Chemicals such as tar, ammonia (NH_3), benzole and sulphur are recoverable from raw COG to be sold. However, the trading of these chemicals has culminated to little profit yields over time. Hence, alternative economically viable applications such as energy, liquified natural gas, power generation, reducing gas in DRI production and methanol are of increasing interest [33], [35]. COG cannot be used directly in its raw state from the coke ovens. Gas recovery and pre-treatment processes are thus required [32].

[14] 1 Exajoule (EJ) = 1 x 10^{18} Joules (J)

Coke oven gas recovery and pre-treatment

An important step of the COG recovery and pre-treatment is gas cleaning. This is required since untreated COG clogs pipes, burners and other equipment [32]. COG treatment plants on integrated steel facilities are thus important for this purpose [35]. The COG cleaning process involves a network of stages.

The raw gas is first detarred and cooled down from temperatures in excess of 800 °C to 25 °C in primary coolers. A tar separator receives water and tar, from which crude tar gets recovered. Hydrogen sulphide (H_2S) and NH_3 are scrubbed in subsequent stages, while benzole is removed and recovered for further applications. The scrubbed gas transfers to a benzene-toluene-xylene (BTX) scrubber, from which purified COG exits [35].

In a parallel stage, a deacidifier/stripper unit removes H_2S and NH_3 from the wash water through desorption. The wash water is then returned to the gas scrubber. Subsequent steps crack NH_3 into hydrogen and convert H_2S into sulphur. Tail gas gets recycled to the raw gas stream. Excess water from desorption stage is discharged to the biological effluent treatment plant to be purified. At the treatment plant, decomposition of nitrogen and hydrocarbon occurs. A schematic diagram of the COG cleaning process is shown in Figure 7 [35].

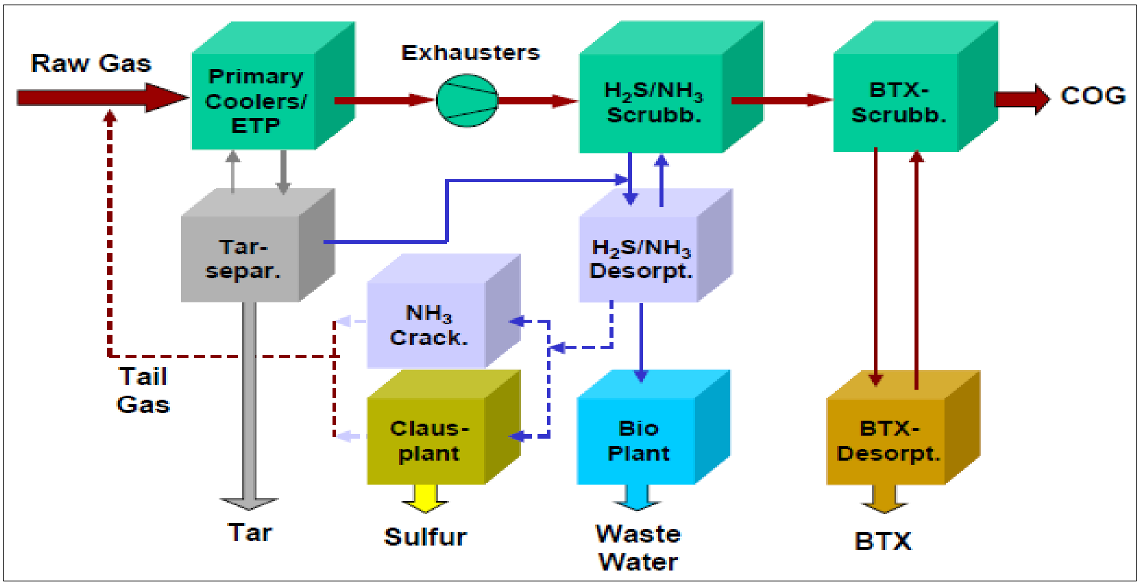

Figure 7: Simplified process flow diagram for a COG treatment plant. Taken from [35]

Challenges associated with coke oven gas utilisation

China has an annual COG production of 70 billion Nm^3. Of this, only 20 % is utilised as energy. Due to a lack of strategies to efficiently utilise COG, most of it gets flared to the atmosphere.

This is a serious wastage of energy, which also results in environmental pollution consequences [33].

The utilisation of COG as an energy source is not a straightforward concept. The fluctuating properties of COG impose operation restrictions regarding its usage. COG fluctuates in gas quality, CV, gas composition, cleanliness and supply volume. The cleanliness is a major hindrance to the optimal usage of COG. This is because the impurities contained in the gas clog gas analysing equipment that quantify its energy content. Without proper quantification, energy is inefficiently managed.

The supply volume and quality are also affected by the steel production and gas consumption instabilities of the facility [30]. The energy balance of integrated steel plants is strongly affected by variations in the yield and CV of COG, which depend on the nature of coal used in the coke production process [39].

Coal sourced from different locations at different times possess different properties. The fluctuations are a result of the changes in quality of the coal used, the production stage during which a particular gas sample is generated and the efficiency of downstream gas treatment processes [32]. This unstable nature affects the reliability of COG as a fuel source. Therefore, plants and subsequent processes that use COG need to strategically overcome these associated challenges for an improved utilisation and energy performance of the gas.

1.2.3 Steel reheating furnaces

Steel milling operations transform semi-finished steel products into finished products. In hot-rolling processes, steel mills are equipped with reheating furnaces to elevate the material temperature to a state of plastic deformation prior to rolling [41]. Reheating furnaces are critical equipment, the efficiency of which determines the quality of the end product, and the total operational costs of the mill [42].

The furnaces are used to heat steel stock in the form of billets, blooms and slabs. Natural gas and by-product gases are consumed for production energy [41]. The steel material is heated up to temperatures in excess of 1 250 °C The heating process is continuous, with the steel stock charged at the entrance, heated and then discharged at the exit of the furnace. The stock can be charged at ambient or pre-specified elevated temperatures, a process referred to as hot charging [43].

A reheating furnace is typically compartmentalised into zones, through which the stock moves at a controlled pace while getting heated. These zones are identified as the preheating zone

(PHZ), heating zone (HZ) and soaking zone (SZ), with that order of material passage. Depending on the furnace design, the HZ and SZ can be subdivided into the top and bottom, and east and west zones, respectively. Heating mainly takes place in the PHZ and HZ, while stock temperature homogeneity is achieved in the SZ to enhance rolling temperatures [43]. A schematic diagram of a typical steel reheating furnace is shown in Figure 8.

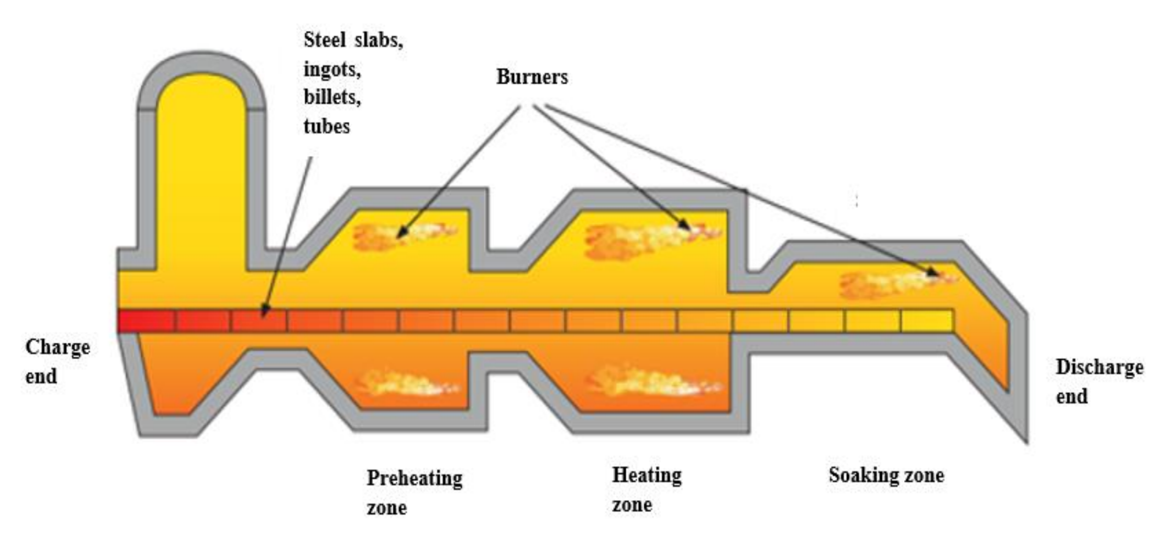

Figure 8: A schematic diagram of a steel reheating furnace [15]

Minimisation of fuel consumption coupled with maintenance of a homogenous material thermal soak is required for optimal operations of reheating furnaces. The heating of stock inside the furnace occurs mainly through convection and radiation. The reheating process presents the bottleneck for maximum production. Reheating furnaces contribute 70 % towards the energy consumption of hot-rolling processes [44].

1.2.4 By-product gases for energy efficiency: Best available practices

The cost of energy contributes to about 20 – 40 % of steel production costs [45]. The International Energy Agency indicated the need for a widespread application of best available practices (BAPs) to combat operational challenges and associated costs faced by the industry [24]. Some of the identified challenges include the fluctuation in the availability and quality of raw materials, industrial competitiveness and carbon leakage [16].

[15] Ametek-land. [Online] Available: amatek-land.com. [Accessed 2019-03-03]
[16] Kira West, International Energy Agency (IEA), "Energy Technology Perspectives 2015: Iron & steel findings" [PowerPoint Presentation], 12 May 2015. [Online] Available: www.oecd.org. [Accessed 2019-02-11]

A total energy consumption saving potential of 20 % was estimated for the iron and steel manufacturing industry in 2012 [13]. The adoption and application of BAPs, particularly in older plants, will afford steel producers an opportunity to take full advantage of the potential energy savings. Energy saving potentials of 4,4 GJ/t and 3,8 GJ/t crude steel have been reported for the world and South Africa, respectively [13].

Energy efficiency technologies for iron and steel plants have been extensively investigated and information on their outcomes and applications availed by researchers. The following section will briefly review and collectively summarise existing and emerging energy efficiency technologies. BAPs applicable to the relevant production stages in the BF – BOF and EAF production routes will be reviewed.

Practices involving utilising by-product gases as sources of energy in steel hot-rolling milling operations will also be reviewed. The detailed descriptions of the reviewed BAPs, the fuel and electricity saving quantification, capital investment and the estimated payback period are given in Appendix B.

Best available practices for by-product gas utilisation in the steel industry

The steel industry has various BAPs in place for the purpose of improving on energy efficiency performance. This section will review the BAPs involving by-product gases utilisation for energy efficiency. A summary of the identified BAPs for energy efficiency applicable in the various steel operation sections is presented in Table 2.

Table 2: BAPs for energy efficiency using by-product gases in integrated steel operations. Adapted from [11], [13], [23], [42], [46]

Integrated steel operation section	Best available practices	Description	*Applicability and feasibility code
Sinter production	Waste by-product gas heat recovery	By-product gases recycled to sinter bed and sinter cooling gases used to heat air used for oxygen enrichment.	-
Coke production	Coal moisture control	Using residual waste heat from COG to dry coke producing coal.	C, EX
	Additional use of COG	Reusing COG as fuel in the coke ovens for the reduction of natural gas usage.	C, EX

	Non-recovery coke ovens	Heat recovery from raw COG and electricity cogeneration for the prevention of air and water pollution from the by-products recovery process.	C, EX
	Variable speed drive (VSD) COG compressors	Reduction of gas compression energy using VSD COG compressors for pressure increase within COG transportation internal grid.	C
Ironmaking (blast furnace)	Injection of COG and BOFG	Reducing the consumption of coke by injecting COG and BOFG for fuel energy requirements. An additional benefit is a reduction in CO_2 emissions.	C
	Recovery of blast furnace gas	Recover blast furnace gas to be used as an energy source in auxiliary blast furnace systems and other compatible applications on the facility.	C, EX
	Recuperator hot-blast stove	Preheating blast furnace combustion air through heat exchange with the BFG.	C
	Recycling of BFG	Recycle BFG for use as a fuel source in the blast furnace.	-
Steelmaking (BOF)	BOFG and sensible heat recovery	Heat recovery from BOFG for boiler applications, power production and as a fuel source in the BOF.	C
Steelmaking (EAF)	By-product gas post-combustion	Post-combustion of the by-product gases from the steel bath to preheat scraps or EAF ladle steel.	C, EX

The following section will review BAPs and practices that are applicable for energy efficiency in steel hot-rolling milling operations. These practices are applicable to both the BOF and EAF steel production routes [42]. The summary of the applicable BAPs is given in Table 3.

Table 3: BAPs for hot rolling operations energy efficiency. Adapted from [11], [13], [23], [42], [46]

Steel plant section	Best available practices	Description	*Applicability and feasibility code
	Proper reheating temperature	Adjusting the furnace temperature per requirement of reheated material. However, this	-

Hot rolling processes		practice has an impact of overall energy consumption increase.	
	Avoid overloading of reheating furnace	An overloaded furnace results in poor heat transfer. Increased energy consumption and losses are the resulting effects.	EX
	Hot charging	Charging steel at elevated temperatures into the furnace. Production scheduling has a major impact on the energy savings due to this practice.	EX, N, S
	Process control in hot strip mill	Improved combustion processes control. Can be achieved by installation of VSDs on combustion fans and furnace oxygen levels control.	EX
	Recuperative burners	Preheating combustion air with heat recovered from furnace by-product gases.	C, EX
	Flameless burners	Fuel is combusted in a diluted oxygen environment using the recirculation of internal by-product gases. This offers better thermal efficiency and uniformity, and reduced fuel consumption.	C
	Furnace insulation	Reduction of heat losses through walls by applying coatings and ceramic low-thermal mass insulating materials.	C, EX
	Walking beam furnace	Using a walking beam furnace instead of the pusher-type for reduced energy consumption.	C, EX, N
	Heat recovery to the product	Preheating of steel material before charging using heat recovered from the furnace by-product gases.	C, N
	Waste heat recovery from cooling water	Heat recovery from hot strip mill to produce low-pressure steam. However, this measure increases the consumption of electricity.	C, P

**Applicability and feasibility codes* [42]*:*

C = Costs and/or use practicality at all facilities will be affected by site-specific variables.

EX = Many existing facilities have already widely implemented this technology.

S = Technically appropriate equipment configurations and specialised processes only.

N = Feasible for new units only.

P = Process still in research and/or pilot stage.

Discussion and summary

The energy efficiency technologies and practices briefly reviewed have been shown to be beneficial at certain iron and steel facilities around the world. It is assumed that these practices could be globally adopted and applied at any other facility, given the present production levels. Cost savings, increased productivity and competitiveness have been identified as important energy efficiency improvement drivers [47].

A majority of the identified and reviewed practices in Table 2 and Table 3 are based on the U.S. steel industry. It can be seen from these tables that most of the technologies have been assigned an availability and feasibility code of "EX". This entails that the particular technology has already been implemented widely in many steel facilities [42].

Many of the technologies were also assigned the "C" code, entailing that implementing such practices depends on costs and practicality at any given site. Technologies coded "P" indicate that the technology is still in the research and/or pilot stages, while "N" means feasibility was only seen for new units. If the code "S" is assigned, it means that the process is specialised and requires technically appropriate equipment configurations [42].

Different country- and plant-specific influences may hinder the successful adaptation and implementation of energy efficiency measures. These include, but are not limited to, economic feasibility, installed facility specifications, political issues, regulatory and social factors, and transition fees [13], [24].

Organisation for Economic Co-operation and Development (OECD) [47]

Despite the available potential to improve energy efficiency, research has also shown that steel producers do not always choose to implement these measures optimally. The Organisation for Economic Co-operation and Development (OECD) conducted a survey to investigate the reasons and barriers that hinder some steel producing companies from implementing energy saving measures [47].

Long investment payback periods were identified as the leading hindrance, despite available interest and capabilities in an energy efficiency project. This was followed by lack of capital and government incentives. Meanwhile, challenges such as lack of technical expertise, little or no government policy and high risk of investment were identified as least hindering [47].

Considering the present state of the South African steel sector, it will be unfeasible and impractical to consider implementing technologies that require capital cost investments and long payback periods. Instead, measures based on operational changes and improvements with minimum or no capex on existing processes, while yielding immediate savings, are sound and more beneficial. The need for capex increases the strain and pressure onto an already financially struggling domestic market [6].

1.3 Literature review

1.3.1 Preamble

The previous sections have established that the South African iron and steel industry is under financial pressure. This is due to increasing primary energy and operational cost, and a poor global market performance, among other factors. This chapter provides a comprehensive literature review of relevant sources focusing on improving by-product gas utilisation for energy efficiency in steel operations.

1.3.2 Literature review focus areas and evaluation criteria

Focus areas

The literature review covers an analysis of different, relevant methods that have been identified and applied for improved utilisation of by-product gases in various industrial disciplines. This will be followed by an evaluation of existing, relevant research studies on energy consumption and efficiency improvement in steel reheating furnaces. Lastly, existing solutions for reheating furnace energy efficiency through improved by-product gases utilisation will be identified and discussed. The focus areas are illustrated in Figure 9.

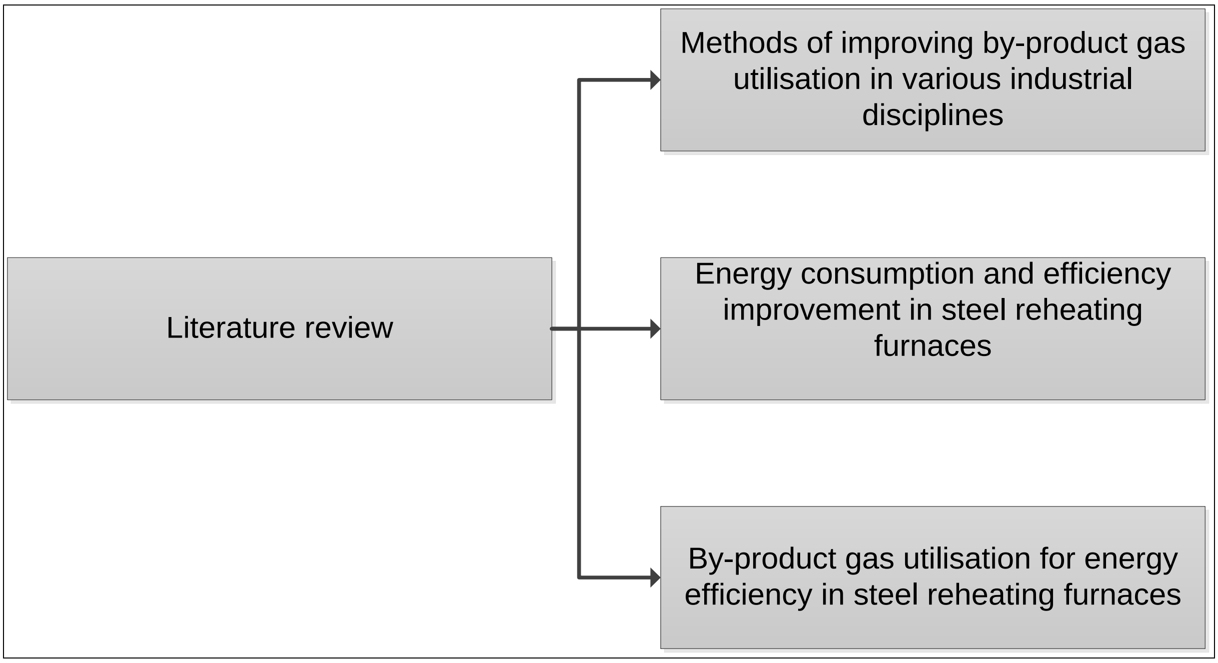

Figure 9: Focus areas for critical literature analysis

Evaluation criteria

The utilisation of by-product gases as alternative materials and energy inputs into manufacturing processes is not a new concept for the industrial sector. However, an improvement in the utilisation of by-product gases is a measure yet to be exhausted [62]. In this regard, the literature review looks at studies that have focused on different ways to improve by-product gas utilisation for energy purposes. The applicability of the various study solutions to the iron and steel industry is vital, since this industry is the subject of this study.

Following that reheating furnaces are the biggest energy consumers of energy in steel milling operations, study solutions focusing on the improvement of their operational efficiency are vital to this study. In Section 1.2, it was shown that COG is competitive with natural gas and it possesses the ability to meet high temperature application requirements. Therefore, studies that focused on improving the combustion of COG were found relevant.

A critical factor for effective combustion is the air-fuel ratio. For nonconventional fuels, such as by-product gases, determining the appropriate air-fuel ratio at any given instance is a challenge, owing to their fluctuating nature in quality and energy content. Real-time solutions for air-fuel ratio adjustments were thus considered.

Practical experience on a steel facility has shown that as a result of an inefficient gas cleaning process, installed equipment for measuring CV of COG frequently get clogged due to the remaining heavy oils and tar. The unavailability of CV data affects furnace operations. Hence, studies on methods for estimating unavailable CV of COG were evaluated.

In earlier sections of this document, the present financial strain the local steel industry is faced with was emphasised. Hence, solutions that require additional investment costs are considered impractical. In this regard, operational change-based strategies are vital because changing furnace control strategies do not require changes to the existing hardware [48].

Lastly, a solution proven feasible for one facility will not necessarily work for another. Factors such as resources availability, technical ability and willingness by personnel, country- and plant-specifications, among others, come into play. Hence, relevant solutions that have been found to be applicable, and not necessarily unique, to a South African case study were considered.

The limitations identified from the literature review were thus used for deriving and formulating the need for this study and the novel contributions, thereof. This will be done by evaluating and critiquing the literary sources, while highlighting their shortcomings. In this regard, the literature critique and evaluation criteria were structured as follows:

- Utilisation of by-product gases.
- Application in the iron and steel manufacturing industry.
- Focused on energy efficiency in steel reheating furnaces.
- Focused on improving coke oven gas combustion in steel reheating furnaces.
- Furnace temperature control and stabilisation using air-fuel ratio control.
- Estimation of unknown calorific value of coke oven gas.
- Operational change strategy without additional investment costs.
- South African case study application.

1.3.3 Methods of improving by-product gas utilisation in various industrial disciplines

The effective utilisation of energy resources is a key strategy to the reduction of energy-related costs. By-product gases have found a wide application across the various process stages in integrated steelmaking facilities. The use of by-products is beneficial to energy and raw material savings [12]. The recovery of energy from waste products and process streams is seen as one of the most viable strategies to suppress the threat of increasing energy costs [62].

Utilisation of by-product gases varies between countries. For instance, while in China by-product gases are flared, they are recovered and used in Japan and Germany [18]. The improvement in the utilisation of by-product gases has been identified as one of the important technologies to be exploited to assist local steel manufacturers to improve energy and cost savings.

Reviewed literature studies

Zhao *et al*. [30]

In their study, Zhao *et al*. [30] reviewed methods for optimising by-product gas scheduling and distribution in the steel industry. Industrially applicable models for gas scheduling, such as the mixed integer linear programming, neural networks, heuristic search algorithm and high-level architecture were discussed [30].

The review concluded that because of the complexity of large-scale industrial applications, the models are presently insufficient. The study points out that the influence of by-product gas pressure and operation loads on boiler thermal efficiency are major challenges for the models. The balance between accuracy and satisfactory solving speed was indicated as another major shortcoming of these models [30].

Zhang *et al.* [31]

A study by Zhang *et al.* [31] proposed a method to optimally predict and adjust the levels of by-product gas holders. The level prediction models were established for single and multiple gas holders by machine learning methodology. The gas holder model also allowed for the determination of adjustments amounts of by-product gases to maintain safe operating zone levels, where manual operations are usually ineffective [31].

The proposed method was simulated and verified on a case study in China. The method was compared to four other methods, including the manual. The results show that a precise prediction and adjustment of the gas holders were achieved. The gas-holder can be predicted in real-time with high accuracy [31].

Modesto and Nebra [49]

Modesto and Nebra [49] performed an exergo-economic assessment of a power-generating system of a steel mill. The system uses BFG and COG as fuels for electricity and steam generation. Through a case study, it was shown that replacing BFG with COG equally increased both the electric power generated and overall efficiency of the plant [49].

This study has shown that utilisation of by-product gases as fuels in the place of conventional sources, e.g. natural gas and coal, for power generation leads to energy cost reduction. However, the feasibility of this study depends on eliminating and replacing certain process units and fuels. This will have the adverse effects of production output decrease for the facility. The technical challenges associated with the changes in supply and energy content of the by-product gases were not acknowledged and addressed.

Marais [50]

Marais [50] studied the potential for South African integrated iron and steel industries to expand their cogeneration capacity. A framework was developed for applications as a tool for direct decision-making pertaining to the pursuit of potential cogeneration projects. The main drivers for cogeneration pursuit were identified as; the need to become more self-sufficient, electricity tariffs increase, increased pressure to reduce carbon emissions and security of electricity supply [50].

Validation at a local integrated iron and steel company showed a technical parameter correlation in the range of 85 – 98 %. The validation also indicated an alignment with the practices applied at the company. The framework was indicated to be expandable and adaptable to other South African iron and steel companies [50].

The study recognised that the identified cogeneration technologies may require capital expenditure that may not necessarily be provided for by the industry. A recommendation to externally acquire capital investments was brought forth [50]. Projects that require capital investments are not feasible for the present financial status of local steel plants.

Murray and De Kock [51], [52]

Murray and De Kock [51] conducted a techno-economic evaluation for utilising furnace by-product gases as fuel for cogeneration at a South African ferrochrome smelter. The purpose was to determine the amount of electricity that could potentially be produced from the furnace by-product gases. The total off-gas produced volume and its CV were used to determine the energy available for electricity generation [51].

Measurements and calculations of the ferrochrome smelter furnace showed an annual by-product gas production of 150 MNm^3, of which 83 % was available for cogeneration. A CV of 9,1 MJ/Nm^3 was indicated. With a 28 % overall plant efficiency, the potential generation was determined as 88 GWh per annum [51]. This translates into a 12 – 14 % potential reduction in Eskom purchased electricity [52].

For a new plant application, the capital costs of this initiative were estimated as R 491 million in 2015. R 31,3 million in annual operation costs was determined and the economic analyses showed a payback period of 8,65 years [52]. This work confirmed the potential use of by-product gases for electricity generation.

However, the high capital costs and long payback period associated with an initiative of this nature cannot be feasible for adoption and adaptation within the local iron and steel manufacturing sector under the existing circumstances. For an existing plant, this work does not clearly address the technical challenges associated with the fluctuations in by-product gases supply and CV.

Ludick [34]

Ludick [34] focused on the reduction of by-product gases flaring to improve the on-site power generation output for a local steel producer. The impact of this study was a reduction in electricity cost expenditure and an improvement in by-product gas energy management and sustainability through reduced flaring [34]**.**

Ludick [34] developed a controller to determine the electricity generation output following the fluctuations in by-product gas supply. The controller determined gas availability through instantaneous gas-holder levels. After implementation of the controller on a case study, it was shown that a 20 % reduction in flaring was possible. The overall cost reduction performance analysis of this work indicated that an annual cost-benefit of R 4,8 million could potentially be achieved [34]**.**

Venter *et al.* [53]

Venter *et al.* [53] studied the impact of the fluctuating by-product gas production and supply on the steam generation and power output of a boiler house of an engineering plant. An optimisation control algorithm (CA) for the boilers was developed. Two power generation simulations were developed. One was based on the manual operating procedure (MOP) strategy of the plant and the other on the optimised CA [53].

The plant utilised a 5 MW and a 30 MW turbine. By implementing the CA, an improvement in power output and a reduction in tripping frequency of the turbine was realised. The CA showed a potential power generation capacity increase of 3,67 % over the combined capacity of 35 MW when using the MOP strategy. Using an Eskom tariff of R 500/MWh, the plant was indicated to potentially realise annual electricity cost savings of almost R 5 million upon implementation of the CA [53].

Maneschijn *et al.* [18]

Various measures are available for industrial energy consumers to minimise costs associated with the use of electricity. One such measure is load shift. By implementing this measure, consumers on the Eskom MegaFlex [17] tariff scheme stand to achieve electricity cost savings by minimising and avoiding usage during peak periods. Maneschijn *et al.* [18] investigated the potential for a load shift using by-product gas-holder infrastructure on a South African steel plant [18].

The study looked at the use of by-product gases as cogeneration energy inputs in boilers. The gas system was simulated under defined constraints. Plant data and observations were used to validate the simulation. Thereafter, a load shift was simulated by equally increasing and decreasing cogeneration during peak and off-peak periods, respectively. The results indicated that an additional peak generation capacity of 2 MW was possible. If implemented, R 2,3 million worth of annual cost savings could be realised [18].

Ryzhkov *et al.* [54]

Ryzhkov *et al.* [54] studied the efficiency of operating a combined-cycle power plant (CCP) on BFG at Russian metallurgical plants. The goal was to be able to burn BFG without enhancement with higher CV fuel gases such as COG and natural gas or using special flame stabilising measures [54]. The results from calculations performed using a specialised software package were presented.

It was indicated that at roughly 400 MW capacity, a CCP can possibly burn BGF at a high-capacity gas turbine power plant without adding COG or natural gas. However, due to the low BFG CV range, i.e. 2,5 – 8 MJ/Nm^3, system upgrades are required. These include upgrades on the fuel delivery system, combustion chamber and the air compressor due to changes in fuel gas pressure and air volume [54].

[17] Electricity cost division structure into three tariff periods, as available from Eskom, i.e. Peak, Standard and Off-peak [64].

The results indicated that while firing BFG, the CCP can generate 387 MW of power. The required upgrades will need a capital investment of almost $US 600 million (approximately R 8,9 billion) [18]. A payback period of 3.6 years was estimated [54]. The usage of BFG in high temperature applications requires enhancement with higher CV gases.

This necessitates the installation of gas mixing stations. Gas mixing may enhance certain properties of the overall gas, while suppressing others. Hence, specialised methods and equipment are required to ensure the desired resulting effect. Moreover, the investment costs associated with the upgrades make this solution impractical to the present study.

Pugh *et al.* [55]

Pugh *et al.* [55] studied the combustion characteristics of by-product gas blends produced in steelworks using a constant-volume bomb. The spherical flame configuration and the laminar burning speed were used for analysing the combustion performance of the gases. This work tested the impact of COG on improving the combustion of BFG by dampening the effects of compositional fluctuations inherent from blast furnace operational changes [55].

The effect of COG concentrations on the CV of the gas blends was also investigated. The results of this study pointed out that small additions of COG dampened the fluctuations in flame speed experienced under different BFG compositions. The COG also significantly stabilised the combustion process. Further highlights include a stable gas CV, overall increase in energy intensity and stability of operational thermal output [55].

A potential method for improving the utilisation of BFG was given. However, the tests for which the outcomes are discussed were done under ambient conditions, which are not representative of reheating. Gas burners have a compatibility range in terms of the fuel gases burnt. Hence, some design modifications may be required prior to using gas blends.

This study specified the usage of COG as a lower CV fuel enhancer. However, under normal operating conditions, the composition of COG is also prone to fluctuations. Additional equipment will be required for maintaining the specified characteristics. Therefore, this solution is not feasible for the present study.

[18] Converted using the currency exchange rate of 1 USD = 14.93 ZAR. Bidvest Bank Forex Calculator [Online]. Available: bidvestbank.co.za. [Accessed: 2019-08-20].

Summary of literature review findings

The literature studies reviewed in this section focused on improving by-product gas utilisation through the management, distribution and usage scheduling by the various consumers on the facility. Some researchers showed the impact of automated control for improved by-product gas management. This is particularly impactful in addressing the fluctuating supply characteristic of by-product gases. These studies have emphasised that manual operations under the control of human operators subject the plants to missed energy saving opportunities.

Due to their energy content, by-product gases have found extensive applications in on-site power generation. Researchers reviewed under this focus area discussed the electricity potential of the by-product gases in various industrial applications. The use of COG to enhance the energy potential of other lower fuel gases was touched on. The summary of the reviewed literature, highlighting their shortcomings in relation to this thesis is presented in Table 4.

Table 4: Summary of evaluation criteria for methods of improving by-product gas utilisation

Author (s)	Utilisation of by-product gases	Solution application to iron and steel industry	Operational changes strategy without additional investment costs	Focused on energy efficiency in steel reheating furnaces	Focused on improving coke oven gas combustion	Estimation of unknown calorific value of fuel sources	Focused on combustion improvement using air-fuel ratio control	South African case study application
Zhao *et al*. [30]	✓	✓	✓					
Zhang *et al.* [31]	✓	✓	✓					
Modesto and Nebra [49]	✓	✓	✓					
Marais [50]	✓	✓						✓
Murray and De Kock [51], [52]	✓							✓
Ludick [34]	✓	✓	✓					✓
Venter *et al.* [53]	✓	✓	✓					✓
Maneschijn *et al.* [18]	✓	✓	✓					✓
Ryzhkov *et al.* [54]	✓	✓						
Pugh *et al.* [55]	✓				✓			

The gap identified from the review under the current focus area addresses the challenges that are faced by the final end-user of the by-product gas. The end-user still has to manage challenges such as fluctuating gas CV. These shortcomings were addressed by the following novel contribution from this study:

An adopted method for adaptive air-fuel ratio adjustments for steel reheating furnace temperature zones, based on the calorific value of coke oven gas and the current operating conditions of the respective zones.

1.3.4 Energy consumption and efficiency improvement in steel reheating furnaces

Steel reheating furnaces are the second largest consumer of energy on integrated steelworks after the blast furnace. Energy consumption and efficiency improvement of reheating furnaces have been topics of widespread research among role players at various levels [43]. In large steel operations, these furnaces rarely operate under stable and steady state conditions. Their stability is affected by the variety of steel grades, required discharge temperature, required reheating time and steel stock dimensions [43]. This affects their energy efficiency.

The energy efficiency of the reheating furnaces cannot be measured directly due to its complex nature. The complexity of the interlinked mechanisms within the furnace interferes with efficient operations [56]. Researchers have proposed and applied model-based strategies and simulations to study, understand and control the behaviour of reheating furnaces. In this section, literature studies on improving the energy consumption performance of reheating furnaces using modelling are reviewed. Their relevance and applicability to the present study will be assessed.

Reviewed literature studies

Nguyen *et al.* [43]

Nguyen *et al.* [43] used a numerical nonlinear model to predict the thermal behaviour of a walking-beam reheating furnace. Based on the model, a model predictive controller (MPC) was designed for furnace zone temperature set-point optimisation for different temperature requirements. The optimisation was achieved through using the Nelder-Mead simplex method, which quickly declines the objective function [43].

Simulation results based on industrial data illustrated an energy consumption reduction by 5 % and a significant improvement in heating performance. It was also revealed that the controller worked well during transient operations. This study showed the significance of temperature control in the furnace for energy saving. However, further studies on the robustness of the controller were proposed because this parameter of the controller was yet to be investigated. The model and control strategy were not applied on an industrial furnace, hence the results cannot be considered for further applications as such in this study [43].

Santos *et al.* [57]

Santos *et al.* [57] studied the possibility of minimising fuel costs for a reheating furnace by modelling the operation of the furnace as a non-linear optimisation problem. A solution method was developed following a genetic algorithms approach. Implementation of the method and computational simulation results showed the possibility of minimising costs for different production rates and charge temperatures. A reduction in fuel consumption by 3,36 % was shown when practical results were validated with actual data [57].

This study emphasised the criticality of maintaining proper reheating temperatures to achieve the desired metallurgical, mechanical and dimensional properties of the final product. The study essentially used the relation between fuel flow rate and furnace internal temperature for fuel cost minimisation. Mathematical models and optimisation algorithms to establish optimal points for furnace operations were used [57].

The heating efficiency of material is vital for the reduction of stock rejects. The optimised models were used to maintain a controlled reheating process under different process constraints [57]. Process constraints such as varying furnace load and charging temperatures were considered. An improvement in energy efficiency was shown for this study. However, the change in fuel supply and quality was not a considered variable.

Steinboeck *et al.* [48]

Steinboeck *et al.* [48] developed a dynamic optimisation method for controlling the temperature of steel slabs in a continuous reheating furnace. A continuous-time switched nonlinear model was used for the control structure, which uses the furnace zone temperatures as intermediate control variables [48].

Consistent approximation obtained a parametric optimisation problem efficiently solvable with the quasi-Newton method. The temperature trajectories of the furnace and slabs are planned by the optimised method [48]. The study uses high-level and complex mathematical formulations. These require furnace data and variables that may not always necessarily be available or up to specification, especially for older plants. The study focused on slab and furnace temperature control without discussing the associated impact on the energy consumption and fuel supplied.

Wang *et al.* [56]

Wang *et al.* [56] modelled and predicted the combustion efficiency of a reheating furnace by using a soft-sensing method. The authors proposed a model-based optimisation strategy for furnace energy savings. In the study, derived variables for combustion efficiency modelling were proposed. Their impact and significance were ascertained using statistical methods [56].

A non-negative garrote variable selection procedure was employed to propose a modelling and adjustments adaptive scheme for time varying characteristics. Correlation and linear discriminant analysis showed that the air-fuel and temperature-fuel ratios were significant derived variables [56].

The optimisation model was implemented on actual operational data. The results showed that combustion efficiency was maximised by decreasing the gas flow and increasing the air-fuel ratio to the boundary conditions. When the developed soft-sensor model is used to optimise the furnace operation, significant energy savings can be realised [56]. The objectives of this study were met. However, the effects of fuel changes on the combustion efficiency were not effectively addressed and discussed.

Tan *et al.* [58]

In a study by Tan *et al.* [58], a zone method of radiation analysis was used to predict the thermal performance of a large bloom reheating furnace. Based on the method, mathematical zone models were developed to simulate the production environment transient behaviour of the furnace. The net radiation interchanges between the firing sections and enthalpy exchange between combustion products of different sections of the furnaces were accounted for in the models [58].

The models were validated using production throughput rates and plant model data. The results showed a reasonable accuracy of the models when compared to the measured heating profiles of the blooms. One model was indicated to be able to improve the specific heat consumption predictions. Through simulation studies, the response of the furnace to production throughput changes was assessed [58].

The outcomes indicated that the furnace responded differently to the throughput rate changes. The changes also influenced the settling time into the next steady state operation of the furnace. This work assumed that different throughput rates will maintain the same furnace heat distribution profile. However, in practice, the heat distribution is subject to be influenced by changes in production throughput, among other factors.

The study suggested re-running simulations on isothermal computational fluid dynamics (CFD) modelling [58]. CFD software and modelling are highly accurate, however they require large computing space and time. Furthermore, this study mainly focused on changing throughput as the variable causing transient furnace behaviour. The change in fuel supply was not indicated. This solution is useful for improving the performance of the furnace under transient production conditions; however, it is not applicable for the present study.

Hu *et al*. [59]

The energy consumption and heat transfer performance of a reheating furnace are significantly influenced by its operating conditions. These include, among other factors, the stock material properties, furnace scheduling, furnace firing pattern control and throughput rate. To ensure temperature uniformity during stock heating and consistent product discharge temperatures, reheating furnaces are equipped with tailored MPC systems [59].

Hu *et al.* [59] argued that the performance of such model operating systems rely on designed operating conditions, and cannot cope with transient furnace operations caused by unforeseen disturbances. For that reason, the authors used a zone method-based model for a non-linear dynamic simulation of an actual episode of a transient operation of a reheating furnace. The model was amalgamated with a self-adapting predictive control scheme. For this study, non-uniform batch scheduling and production delays were encountered [59].

Experimental results showed a discrepancy of about ± 10 °C in model predicted stock discharge temperatures compared to actual measurements. It was indicated that the proposed control scheme had the capability to respond to operational changes by dynamically predicting and adjusting the set-point temperatures of the furnace. Simulation results also suggested that adopting the new control scheme would perform better than the existing reheating model under transient conditions [59]. The impacts of transient operations were addressed by this study solution. However, the change in fuel quality was not considered.

Wang *et al.* [60]

Oxygen enhanced combustion techniques have seen increased applications in reheating furnaces. By partially or completely reducing the concentration of nitrogen in combustion air, improved thermal efficiency and productivity can be realised. Wang *et al.* [60] studied the effect that oxygen enrichment concentrations in combustion air has on the thermal efficiency, energy consumption per tonne of steel and production rate of a billet reheating furnace [60].

The oxygen concentrations were studied. The results of the study show that generally, an improved heating rate, reduced CO_2 emissions, and reduced furnace residence time of billets are achieved with oxygen-enriched combustion. A higher slope of production and thermal efficiency increase were observed in the range of 21 – 45 % oxygen concentrations [60]**.**

The energy consumption at 21 % oxygen concentration was determined to be 1,18 GJ/t steel. This was used as the baseline for the furnace. The consumption was reduced by 8,5 % to 1,08 GJ/t using combustion air with 45 % oxygen. At an annual production rate of 2,4 Mt, the existing furnace was estimated to save 6,4 x 10^6 m^3 natural gas [60]**.**

The implementation of this study solution requires the installation of air separation units (ASU) or the outsourcing and purchasing of oxygen from a third party. A fixed air-fuel ratio was used for the experiments, and a significant presence of excess oxygen in the flue gas was indicated by the authors. The presence of excess oxygen increases oxidation rate on the surface of the billets, resulting in the formation of mill scale. This may compromise the quality of the steel.

Jha and Singh [61]

Jha and Singh [61] assessed the energy efficiency of a reheating furnace for an integrated steel plant using the process heating assessment and survey tool (PHAST). The assessment involved the identification of energy loss areas in the furnace and the loss quantification, thereof. Measured structural data and collected production data were used as inputs into the PHAST software tool. The furnace consumed BFG as fuel gas [61].

The outcomes of the assessment indicated that the case study furnace was 45 % efficient on its energy usage. The biggest losses were attributed to flue gases, which accounted for 40 % of the total energy consumption [61]. This is a useful method to identify and prioritise energy saving measures that will enhance energy efficiency. The study discussed some areas for efficiency improvement in this regard, which involve furnace structural and operational changes. However, the improvement strategies were not detailed, and the effects of gas supply and energy content changes were not considered.

Sun *et al.* [62]

Sun *et al.* [62] worked on the optimisation of a combustion control scheme of a steel reheating furnace. The optimisation was based on the steel pull rate, billet surface discharge temperature and flue gas oxygen concentrations as parameters that had a direct impact on the furnace temperature. The application of the scheme on a mill reheating furnace proved feasible. Improved product yields, as well as reductions in billet loss, fuel consumption and environmental emissions were realised [62].

This study was based on using oil as the fuel consumed by the furnace. Challenges associated with sudden changes in fuel supply and use were not dealt with. Another drawback of this study is the need for flue gas analysers for the measurement and control of the residual oxygen as an optimization parameter. Flue gas analysers are costly and involve intensive maintenance.

Chen *et al.* [63]

Stable furnace operations promote energy efficiency and savings. Chen *et al.* [63] studied the fluctuation characteristics of gas consumption in various regions within a billet reheating furnace. An energy apportionment model was used to develop a system analysis method for the degree of fluctuation of the billet region gas consumption. The study focused on the fluctuating characteristics of gas consumption with respect to billet loading temperature into the furnace and the residence time [63].

The gas consumption was indicated to have high fluctuations in low temperature regions, while the fluctuations were smooth in high temperature regions. It was also illustrated that a more volatile gas consumption was seen for lower furnace loading temperatures and for a mixed charge load.

For reduction in the fluctuations of the furnace gas consumption, it was suggested that the furnace be operated on a controlled production rhythm, the furnace loading temperature be improved and a positive pressure operation stability be maintained. The furnace loading plan can be optimised by alignment with existing market orders [63].

This study discussed the fluctuations in gas consumption in different regions of the furnace as a function of production rhythm and charging temperature. The limitation of the study lies in that the influence of the changing input fuel gases on the consumption was not considered. Different fuel gases show different consumption profiles under various operating conditions.

Summary of literature review findings

The literature sources reviewed under this focus area have shown that energy consumption and simulation models are a necessary tool for characterising furnace behaviour and performance. Some of the aspects that were identified as having a significant impact on the energy efficiency of the furnace, and, therefore, required detailed studying for considerable performance improvement include [63]:

- Furnace energy consumption characterisation;
- Production scheduling and optimisation;
- Temperature profile and characteristics of the furnace load;
- Efficient process control algorithms;
- Combustion and thermal efficiency and improvement; and
- Waste energy utilisation.

Table 5 shows the evaluation summary for the reviewed literature with respect to the focus area of energy consumption and efficiency improvement in steel reheating furnaces.

Table 5: Summary of evaluation criteria for energy consumption and efficiency improvement in steel reheating furnaces

Author (s)	Utilisation of by-product gases	Solution application to iron and steel industry	Operational changes strategy without additional investment costs	Focused on energy efficiency in steel reheating furnaces	Focused on improving coke oven gas combustion	Estimation of unknown calorific value of fuel sources	Focused on combustion improvement using air-fuel	South African case study application
Nguyen *et al.* [43]		✓	✓	✓				
Santos *et al.* [57]		✓	✓	✓				
Steinboeck *et al.* [48]		✓	✓	✓				
Wang *et al.* [56]		✓	✓	✓				
Tan *et al.* [58]		✓	✓	✓				
Hu *et al*. [59]		✓	✓	✓				
Wang *et al.* [60]		✓		✓				
Jha and Singh [61]	✓	✓	✓	✓				
Sun *et al.* [62]		✓	✓	✓				
Chen *et al.* [63]		✓	✓	✓				

The major drawback of the literature sources reviewed under the current focus area is the extensive use of models using specialised software packages. The modelling of the furnaces using these packages require vast amounts of detailed and accurate data, which is not always available for older steel plants.

Additionally, the use of models requires specialised knowledge by personnel. Software packages such as MPC, CFD and PHAST were noted in the review. The use and complete reliance on modelling and operational interventions using special software is costly to implement and maintain. This is due to the need for continuous engagement with experts and consultants when malfunctions arise [64]. This leads to occasions of plant standings and inevitably, production delays.

Swanepoel [64] emphasised the need for simplified solutions for semi-skilled personnel with limited specialised knowledge of processes. For this study, such personnel are the furnace operators, to whom the plant's custodianship is under for most of the time on day-to-day industrial operations. This is not to disregard the significance of using these models and specialised software packages for energy efficiency improvement in industrial operations. However, informed decision making for manual overriding as back-up for the malfunctioning of systems is required.

The gap identified from the literature findings for the current focus area gives rise to the following novel contribution:

A unique and newly developed control philosophy for use by furnace operating personnel with less knowledge and expertise to make informed decisions for air-fuel ratio adjustments, instead of using the trial-and-error method.

1.3.5 By-product gas utilisation for energy efficiency in steel reheating furnaces

In this section, study solutions that focused on improving the utilisation of by-product gases as fuel sources in steel reheating furnaces were reviewed. Interest was given to those studies that focused on COG, for reasons emphasised upon in earlier sections.

The efficient utilisation of any combustible fuel source relies on the knowledge of its energy content. This holds true for by-product gases. Integrated steel making facilities usually have installed equipment such as Wobbe analysers and mass spectrometers to directly measure the CV of by-product gases.

Considering COG, it is not unusual for the gas cleaning process to be inefficient, hence traces impurities such as tar, oils and dirt remain composed in the gas. These impurities tend to clog the measuring equipment. In such instances, inaccurate or unavailable CV data becomes a challenge to be dealt with. Alternatively, various CV estimation tools for hydrocarbon fuels are available in literature.

Under this focus area, this section reviewed solutions to challenges including:

- Fluctuating by-product gas supply, quality and CV;
- Estimation of unknown CV of fuels;
- Combustion control and improvement of by-product gases; and
- Furnace temperature stabilisation.

Reviewed literature studies

Van Niekerk [9]

Van Niekerk [9] addressed the effects of changing fuel supply on the cost performance of reheating furnaces on purchased fuel gases. The author studied the individual energy consumption of reheating furnaces that were configured in a network. The study addressed the challenge of by-product gas distribution during supply shortages, which are a frequent occurrence in aged South African steel operations [9].

A solution methodology was developed to optimise and prioritise by-product gas distribution in real-time according to the energy efficiency and workload of the furnaces. The methodology was validated through a case study on a South African steel rolling operation [9].The operation consumed a combination of natural gas and by-product gases at 38 % and 62 %, respectively.

Results from a test period showed a possible daily savings on natural gas of up to 13 %. Further assessment of the results showed that when operational restrictions were not considered, an overall natural gas consumption improvement of 4 % was possible. Otherwise, a 3 % consumption improvement was shown for an all data inclusive scenario. At 4 % natural gas consumption reduction, an annual cost saving of R 2,3 million was projected [9].

By-product gases do not only change in supply, but with quality and energy content. This study did not further address the implications and effects of by-product gas supply and quality changes for the ultimate end-user, i.e. combustion in the reheating furnaces.

Schalles [38]

The work by Schalles [38] reviewed by-product gas combustion system design options and the related impacts on combustion performance, flame temperature, emissions and energy efficiency. The author discussed aspects to be considered when selecting and designing combustion equipment for high temperature furnace operation applications when using by-product gases compared to conventional high CV fuel gases [38].

Test results from various reheating furnaces pointed out that fuel pressure and CV limitations on the combustion system requirements significantly affected the overall economics of by-product gas usage. The study used CFD modelling to evaluate the effects of fuel-switching. It was found that low CV fuel gases are easy to ignite, and flame stability is maintained. This is on condition that the fuel nozzle design allows for velocities below the blow-off point [38].

The combustion control system requires a fixed Wobbe Index and combustion air requirement index meter for online air-fuel ratio control and corrections [38]. The outcomes of this study review are useful in that they are based on the practical experiences of the author. However, practical considerations for individual plants still need to be evaluated for feasibility. The study shows reliance of using equipment to determine the combustion properties of COG. However, it has been shown that gas analysers are prone to clogging in such applications.

Caillat [32]

Caillat [32] conducted a study to valorise the utilisation of by-product gases in integrated steel milling operations. Two energy-intensive components equipped with burners, i.e. reheating furnaces and annealing lines, were the subject of this work. The author indicated that when using by-product gases, the constant variations in composition and physical characteristics are the biggest challenges against their optimum utilisation [32].

As such, high accuracy of burner settings, e.g. very low excess air, require additional process monitoring equipment such as gas analysers and gas mixing stations. Calibrated orifice plates and pressure control systems do not suffice for burner settings when utilising by-product gases. Hence, adjusting the combustible characteristics of the entire furnace is more convenient than for individual burners. Entire furnace characteristic adjustments for constant excess air include either keeping a constant heating value, Wobbe Index or combustion air requirement index [32].

Cuervo-Piñera *et al.* [37]

A Europe based study by Cuervo-Piñera *et al.* [37] realised a successful enhancement of BFG usage in steel reheating furnaces. The study addressed constraints that are inherited from the lean fuel gas nature of BFG, which inhibit its high temperature applications. The authors' work applied innovative preheated fuel gas burner technologies to design and manufacture burners for 100% BFG usage. The technologies are, namely, flat-flame burners, double regenerative air-fuel and oxy-fuel burners. The technologies were tested on both pilot and industrial scales [37].

The outcomes revealed that when the BFG was preheated with the flue gas stream heat, the reheating furnaces reached typical operating temperatures. This was achieved without enrichment with natural gas. NOx emissions were also kept beneath the European regulation threshold. Safe application guidelines for technical and economic issues; and guidelines for existing furnaces retrofitting were defined. A numerical set-up for BGF firing was defined using computational fluid dynamics (CFD) modelling [37].

The solution to this study is hardware installation based, which is associated with capital costs. For financially strained steel operations, control-based operational changes solutions are more cost effective and feasible. The solution does not discuss the impact of changes in gas supply and quality. The use of CFD models is complex and the required computational times are long.

Van Niekerk *et al.* [41]

A methodology to optimise gas distribution for a multiple furnace network was developed by Van Niekerk *et al.* [41]. The furnaces consumed process by-product and purchased gases. The manual operation method in place for gas distribution resulted in inefficiencies and increased associated operational costs due to the complexity of the system. Regression models for the different furnace gas consumptions were developed and used for energy cost reduction. The basis of the study solution was to allocate the expensive gas to more efficient furnaces [41].

Validation of the method through a case study at a South African integrated iron and steel facility presented an opportunity for R 20 million in annual energy cost savings. It was indicated that the distribution optimisation depended on the energy efficiency and load of the various furnaces. The authors indicated the need for adapting a real-time optimisation solution to implement such a model [41]. The study solution is useful and can further be adapted for gas distribution optimisation in multiple-zone furnaces.

Han *et al.* [65]

Han *et al.* [65] studied the effects of oxy-fuel combustion applications i.e. substituting air with oxygen, on the efficiency enhancement of a reheating furnace following a numerical approach. Their work compared the thermal efficiency of various cases of oxy-fuel and air-fuel combustion using COG. The 4-gas and the modified 5-gas weighted sum of grey gas models (WSGGM) were used for the analysis of the slab heating performance of the oxy-fuel and air-fuel cases, respectively [65].

The results pointed out that at equal fuel-feed rates of oxy-fuel and air-fuel, the oxy-fuel showed a higher medium temperature. This was associated with a higher adiabatic flame temperature. The oxy-fuel combustion demonstrated a 1,5 times larger rate of total radiative heat transfer to the slabs. A significant difference in slab discharge temperature was also seen, with oxy-fuel showing superiority [65].

The authors indicated that it requires 1,54 times more fuel input for the air-fuel combustion to deliver the same slab discharge temperature. An overall higher fuel efficiency of 54 % was observed for the oxy-fuel combustion than for the air-fuel [65]. This study showed a plausible solution to furnace efficiency improvement through replacing air with oxygen. However, the use of pure oxygen incurs additional costs, which was states as impractical for the current financial standing of the local steel industry.

Törnbom [66]

Törnbom [66] studied the feasibility of reducing the fuel costs of a reheating furnace by replacing heavy oil fuel with BFG. The work focused on different methods in which BFG can be enhanced for combustion efficiency improvement in high temperature requirement processes, since the gas is of a low CV. Preheating and oxy-fuel technologies were considered and assessed for feasibility [66].

The study was conducted through mass and energy balance models using real furnace data inputs. Different case studies were created by considering the combustion of BFG in various mixed ratios with COG, while using air or oxygen as the oxidiser. The required temperature to which each combustion combination needs to be preheated was determined [66].

The results indicated that BFG with air required to be preheated to the highest temperature. Meanwhile, the highest adiabatic flame temperature was shown for BFG combusted in pure oxygen, while combustion in air was the least favourable. This study also indicated a fuel cost reduction potential by 44 %. However, investment costs equivalent to R 162 – 215 million were estimated, with a payback period of 3 – 4 years [66].

The solution approach taken by this study is practical for by-product gas utilisation in reheating furnaces. However, the use of oxygen is associated with additional costs from either purchasing the gas from a third party or operating an ASU on-site. Taking the present economic strain faced by local iron and steel manufacturers, large capex-based solutions are not feasible.

Steinboeck *et al.* [67]

Steinboeck *et al.* [67] reviewed several control strategies for saving energy in continuous reheating furnaces. The occurring energy flows and efficiencies of these furnaces were analysed. The study discussed the connection between energy savings and emission reduction. For a case study, a nonlinear MPC for slab temperatures was implemented on an industrial slab reheating furnace. A zone-based PI-control system that was used for decades was replaced. This led to a reduction in primary energy consumption by 9,6 % [67].

The authors indicated that reducing emissions from reheating furnaces is as equally important as saving energy. Energy saving solutions that depend on control strategies are advantageous in that they have no hardware change requirements and they are low-risk solutions. The installations are normally done within very short times, at low costs and with inexpensive rollouts to other furnaces. Moreover, the control strategies can be inter-switched during normal furnace conditions [67].

The control strategies were limited to review under normal furnace operating conditions. The transient behaviour of furnaces was not acknowledged and optimised by the study. A blend of natural gas, COG and BFG was used as fuel, which might have operational limitations for certain furnace burner designs. It was also indicated that the furnace was significantly underutilised during the study. Thus, the results of this study are limited to a conditioned furnace load.

Kilinç *et al.* [68]

A study by Kilinç *et al.* [68] analysed the energy efficiency of an industrial reheating furnace that was fueled by COG and BFG. Energy balances over the furnace and the recuperator were established. An overall furnace efficiency of 62 % was determined. The analysis also identified that reducing excess air, utilising flue gas heat and air leakage prevention in the recuperator will realise significant energy savings [68].

Implementation of the identified initiatives involved the purchase and installation of a flue gas analyser, a new recuperator and an economiser. Post-implementation results increased the overall energy efficiency by 7 %. The biggest contributor to the improved efficiency was attributed to excess air reduction, which declined by 38 %. The recuperator increased the combustion air temperature by 115 °C, an improvement by 36 %. The economiser was able to provide water at 90 °C for human activity usage [68].

The established solution procedure as proposed and implemented by this study is feasible. However, the strategies are associated with capital expenditure, which is not desirable for the present study. Steinboeck *et al.* [67] emphasised that plant owners are hesitant to implement newer hardware based initiatives due to uncertain cost effectiveness and high investment costs.

Flue gas analysers are also maintenance-intensive as they are susceptible to blockages, especially if the by-product gas-cleaning process is inefficient. Multi-zone reheating furnaces combust fuel at unique air-fuel ratios per zone. Hence the determination of a single air-fuel ratio requires further adjustments by furnace operators.

Han and Chang [69]

Han and Chang [69] investigated the effect of various proportions of COG and BFG in fuel gas mixtures have on the thermal performance of an axial-fired reheating furnace. The investigation was performed by analysing the transient radiative slab heating of the furnace with various mixtures. In the study, the finite volume method and WSGGM were used for calculating the radiative heat transfer and the composition-dependent radiation heat transfer, respectively [69].

The test worked entailed varying the COG concentrations in the fuel gas mixtures between 60 – 95 %, with increments of 5 % between successive variants. The results indicated that high COG contents delivered high radiative heat fluxes and slab discharging temperatures. This was attributed to the high CV of the gas mixture. On the other hand, the opposite held true for low COG concentration mixtures. The low COG concentration mixtures, however, demonstrated a superior thermal performance. This was accounted for as corresponding to longer heating times [69].

Through the study, fixed air-fuel ratios of 12,29 and 1,96 were used for COG and BFG, respectively. This suggests that prior composition adjustments were administered for the gases because by-product gases fluctuate due to changes in operational conditions. This requires installation of physical equipment to monitor a constant composition. Such equipment can be maintenance-intensive. The authors also indicated that the calculations required long computation times [69]. Such solutions are not desired and feasible for the purposes of the present study.

Cho *et al.* [75]

Cho *et al* [75] investigated the effect of fuel change on surface combustion performance. They studied the combustion characteristics of COG and liquified petroleum gas (LPG) in a metallic fibre mat, with the former having a lower CV than the latter. Changes in surface temperature and radiant mode while changing the fuel species were studied closely. Experiments were conducted in which the air-fuel ratio and combustion surface loads were varied [75].

The study pointed out that the flame speed of the fuel affects the surface load at which the radiant mode upper limits and peak temperature of the mat were observed. With a higher flame speed, COG showed a widened radiant mode with respect to the changing surface load. When observing the radiant mode dependence on the air-fuel ratio, a gradual decrease with increasing surface load was noticed for both gases [75].

At the same air-fuel ratio, the peak mat surface temperatures were observed at a surface load of 251 and 377 kJ/cm^2h for LPG and COG, respectively. The observations from the study were explained by stating a requirement in balance between mixture velocity and flame speed. It was concluded that fuel gases can be used interchangeably for metallic fibre burners. However, optimal operating conditions remain fuel dependent [75].

The study solely looked at the role that COG has on surface combustion. It was shown that COG can be used and compete in applications in which conventional fuels are normally used. However, the effects and role that the changes in energy content of COG have on combustion outputs were not deliberated upon. The study was also only done on an experimental basis. Its feasibility on industrial scale applications was not indicated.

How CV values are currently estimated

Nomura and Nakagawa [39]

Nomura and Nakagawa [39] conducted a study to predict the yield and CV of COG from coal blends with a high ratio of semi-soft coking coals. They investigated the effects of volatile matter and oxygen content on the yield and CV of COG [39]. A laboratory experimental set-up was used for this study. The results showed that semi-soft coals generally give a low yield and CV of COG.

It was observed that the yield and CV of COG increase with an increase in volatile matter. On the other hand, the COG yield per unit volatile matter decreases with an increase in oxygen percentage in the coal. The results on the effect of oxygen content on the CV were not indicated. The experimental results were used to develop two COG yield prediction methods. One was based on the investigated parameters, and the other was a calculation by modifying Dulong's formula [39].

The methods were validated on an industrial coke plant. The predicted and measured COG yields showed good agreements with respective R^2 values of 0,59 and 0,50 [39]. The purpose of this study was to predict the yield and CV of COG. However, further interest was in the yield prediction than in the CV. The study did not develop a method for the prediction of CV of COG, but only for the yield.

Hosokai *et al.* [70]

Hosokai *et al.* [70] have modified Dulong's equation for estimating the CV of hydrocarbon fuels. In their study, existing estimation equations with methods based on the calorific value of elemental components of fuels were analysed. A total of 406 standard gaseous organic compounds were evaluated using existing estimation equations [70]**.**

The outcomes of the evaluation pointed that Dulong's equation is applicable for energy content estimations, but with limitations. This is due to the equation being developed for estimating the energy content of coals with unidentified structures. The impact of latent heat was also considered as a contributing factor to the limitations. The authors modified Dulong's equation to account for the shortfalls of the original estimation equation. The study indicated that the modified equation gave good descriptions of reported CVs of liquid fuels and coal within the range of 10 – 40 kJ/g [70]**.**

The method developed from this study is feasible for a generic determination of static fuel CVs. The use of the mass fractions of the components imply that there is still a need to install some equipment to measure the concentrations of the components, which have been shown to be maintenance-intensive. This study solution is not feasible for determining the constantly changing CV of fuel sources such as COG.

Kong *et al.* [71]

Kong *et al.* [71] used the manifold and T-pipe models to determine the CV and mix efficiency of a natural gas mixture from a dual gas source distribution station. The natural gases were from different sources, with different compositions. The gas mixing was modelled and simulated using CFD software. The CFD results indicated that the manifold model showed good gas quality than the T-pipe model [71].

The focus of this study was on gas mixing within gas pipe networks, not large volume gas holders. Also, the CV was determined as a function of two components only, i.e. methane and ethane [71]. COG is a mixture of several gas components, with the CO and H_2 being the main combustible gases. The concentrations of the components are subjected to fluctuations. The solution from this study cannot be feasible for the determination of the CV of COG from steel enterprises.

Dale *et al.* [72]

The CV of a gas mixture can be determined by measuring the enthalpy of combustion of its constituents. Dale used the enthalpy of combustion of ultra-high purity methane at 25 °C for the determination of the CV of natural gas. In the study, a constant-pressure gas burning calorimeter with high precision was used. The determined value was comparable to that as accepted for national standards in the United Kingdom (UK) [72].

The method used has been able to determine the enthalpy of combustion with high accuracy. The study found a value of 890,61 kJ/mol, with one standard deviation-based uncertainty of 0,53 kJ/mol. The value compares positively to that indicated by national standards and the International Organisation for Standardisation (ISO) 6976: 1995 i.e. 890,63 kJ/mol [72].

The study solution discussed a possible method for determining the CV of natural gas. However, the ultimate relationship between enthalpy of combustion of methane and natural gas CV was not clearly pointed out and discussed. Also, the ability of the method to cater for gases with fluctuating composition and cleanliness was not indicated. Equipment for measuring CV of gases are prone to blockage when facing by-product gas applications.

The current air-fuel ratio controller technologies available

Wong and Wong [73]

Wong and Wong [73] addressed the challenge of transient air-fuel ratio for nonconventional fuels that are unstable, with a constantly changing composition. In their study, an adaptive air-fuel ratio controller was developed for a dual-injection automobile engine at different operating conditions. The controller was designed with the use of a machine learning method known as extreme learning machine. The engine operated on bio-fuels of various blend ratios. The controller was verified through simulations using a software for industry-level engine simulations [73].

Experimental tests using a spark-ignition engine were conducted for implementation and evaluation of the controller. The tests used throttle positions, different fuel blend ratios and the desired excess air (λ_{des}) value as input parameters. The results indicated that the controller efficiently and effectively tracked and converged towards λ_{des} under the varying conditions. The controller also showed better performance than the engine built-in proportional integral derivative (PID) controller under dramatic fuel-blend ratio changes [73].

The study solution has shown the feasibility for accurate air-fuel ratio adaption under constantly changing fuel compositions. The changing blend ratios can be considered as being similar to changes in CV and composition of COG. However, it was indicated that even though the solution was developed for a dual-injection, the verification was done on a single-injection engine due to unavailability of the former.

Hence, the usability and reliability of the solution on practical, industrial applications cannot be concluded upon. The λ_{des} for engines is determined using feedback from oxygen sensors in the exhaust gas. Oxygen analysers under by-product gas operations are maintenance intensive due to clogging as a result of inefficient gas cleaning processes.

Strommer *et al.* [74]

Strommer *et al.* [74] wanted to accurately control the temperature of the furnace load. Depending on the energy demand of the furnace, a strategy based on controlling the mass flowrate of natural gas and air, hence the air-fuel ratio, to gas-fired industrial furnace burners was developed. This was achieved by applying first principles to mathematically model the fuel branch of the furnace. A combination of a two degrees-of-freedom control strategy and a simple PID-feedback controller was proposed for the furnace to complement the study [74].

Measurement data taken from the plant was used to validate the model, which was indicated as feasible. The results from a simulation study indicated a better control performance by the proposed controller, when compared to a feedforward control strategy alone [74]. The approach to this study solution showed a different perspective to maintaining furnace temperature stability by considering the gas supply pipe network characteristics. However, the changes in the energy content of the fuel gas were not considered.

Summary of reviewed literature findings

The study solutions reviewed in this section presented different approaches to utilising by-product gases in steel reheating furnaces. Some study solutions proposed prioritisation of by-product gas distribution when supply shortages are experienced. Others looked at using preheating technology to elevate the temperature for the gas prior to combustion to enhance its performance. Moreover, others considered blending poor-quality gas with those having a high CV to boost its energy content. The summary of the evaluation is shown in Table 6.

Table 6: Summary of evaluation criteria for by-product gas utilisation for energy efficiency in steel reheating furnaces

Author (s)	Utilisation of by-product gases	Solution application to iron and steel industry	Operational changes strategy without additional investment costs	Focused on energy efficiency in steel reheating furnaces	Focused on improving coke oven gas combustion	Estimation of unknown calorific value of fuel sources	Focused on combustion improvement using air-fuel ratio control	South African case study application
Van Niekerk [9]	✓	✓	✓	✓				✓
Schalles [38]	✓	✓		✓				
Caillat [32]	✓	✓	✓	✓	✓			
Cuervo-Piñera *et al.* [37]	✓	✓		✓				
Nomura and Nakagawa [39]	✓					✓		
Van Niekerk *et al.* [41]	✓	✓	✓	✓				✓
Han *et al.* [65]	✓	✓		✓	✓			
Törnbom [66]	✓	✓		✓				
Steinboeck *et al.* [67]	✓	✓	✓	✓				
Kilinç *et al.* [68]	✓	✓		✓				
Han and Chang [69]	✓	✓		✓	✓			

Hosokai *et al.* [70]						✓		
Kong *et al.* [71]						✓		
Dale *et al.* [72]						✓		
Wong and Wong [73]							✓	
Strommer *et al.* [74]			✓	✓			✓	
Cho *et al.* [75]	✓		✓		✓			

The impurities contained in COG cannot be completely removed during the gas cleaning stage. The dirt clogs gas analysing equipment, which gives rise to the challenge of unquantified energy content of the gas. Some studies that worked on estimating the unknown CV of fuels were reviewed. Their solutions are limited to determining the static rather than time-continuous fluctuating calorific values. None of these study solutions was found to satisfy all the evaluation criteria.

The identified gap showed the need for this novel contribution:

Development of a new generic and integrated producer-to-user solution approach to estimating the unknown calorific value of coke oven gas in integrated steel manufacturing facilities.

1.3.6 Conclusion

This section gave the literature review of the thesis. The study was conducted under three defined focus areas. The initial focus area involved surveying available literature on methods of improving by-product gas utilisation in various industrial disciplines. This was followed by studies that focused on energy consumption and efficiency improvement in steel reheating furnaces. Finally, studies that combined the first two focus areas were surveyed for by-product gas utilisation for energy efficiency in steel reheating furnaces. The critical analysis of the surveyed literature was done using criteria outlined in Section 1.3.2. The shortcomings identified from the review were discussed and used to formulate the need for this study and the novel contributions.

1.4 The need for the study

1.4.1 Problem statement

South Africa is under pressure due to increasing energy and operational costs, and a poorly performing trade market [76]. South Africa contributed 0,35 % towards the global steel production in 2018 [2], which is among the lowest during the most recent decade, as portrayed in Figure 1 (Section 1.1.2). The energy needs of the local steel sector are primarily dependent on coal, electricity and natural gas (Figure 4, Section 1.1.4). The cost of these utilities is predicted to maintain a rising trend in the coming years. Hence, it is imperative for local producers to improve their operational efficiency and reduce energy-related costs to remain competitive.

South Africa produces 80 % of its steel through the BF–BOF route [19], where coal is consumed to produce coke. Coal was reported to contribute 34 % towards the energy consumption of local steel plants in 2015 [16]. A high production of coke directly ties to a substantial supply and availability of COG. COG has shown the highest potential to compete with natural gas, which contributes 30 % to the energy supply of local steel operations. COG has a high energy content and possesses similar combustion properties to natural gas in comparison to other by-product gases, as shown in Table 1. Hence, it is suitable for applications that require high temperatures, such as steel reheating furnaces.

The improved and maximised utilisation of COG can reduce the cost of energy of steel reheating furnaces. A need was identified for an operational change strategy approach to improve coke oven gas utilisation without additional investment capital requirements [77], [78]. From the findings relating to the present financial state of the local iron and steel sector and the availability of coke oven gas as a potential competitor for natural gas, the following problem statement was developed:

"A need exists to develop a reliable method to maximise and improve the usage of coke oven gas in steel reheating furnaces to alleviate operational costs in South African steel manufacturing facilities."

1.4.2 Study objectives

The main objective of this study is to develop a methodology to improve the utilisation of COG and its combustion performance in steel reheating furnaces. Proper air-fuel ratio is a critical factor for effective combustion. A proactive approach to combustion air-fuel ratio adjustments is proposed. This solution will particularly be beneficial for temperature stabilisation during instances of CV of COG fluctuations. It will provide furnace operators with an easy-to-use tool when the need arises to manually override the built-in furnace control system during such instances. To achieve a functional solution, the objectives of this study are listed below:

- Review literature sources for existing measures used for improved by-product gas utilisation and evaluate their outcomes.
- Adapt relevant methods and approaches from literature to the development of a generic and functional adaptive air-fuel ratio determination methodology for various CVs of COG and furnace operating conditions.
- Develop a new and simplified control philosophy for use by furnace operators to adjust air-fuel ratios.
- Develop a novel methodology to estimate the unknown CV of COG.
- Simulate the impact of CV fluctuations and the corresponding air-fuel ratio on the furnace temperature.
- Practically test and validate the air-fuel ratio methodology on a steel reheating furnace case study.
- Quantify the cost-benefit of natural gas-savings upon implementation of the developed solution.

1.5 Novel contributions of the study

Novel contribution 1:

An adopted method for adaptive air-fuel ratio adjustments for steel reheating furnace temperature zones, based on the calorific value of coke oven gas and the current operating conditions of the respective zones.

- Steel facilities are equipped with gas analysers [67] to quantify the energy content of coke oven gas. These analysers measure the CV of COG and provide the ideal, stoichiometric combustion air-fuel ratio. The actual air-fuel ratio used is, however, different from the stoichiometric.
- The actual air-fuel ratio depends on various factors, such as the energy performance of the furnace zones, burner capacity and allowable gas volumetric flowrates [74]. With the use of by-product gases, such as COG, the diameter of the gas pipes reduces over

time due to the build-up of the gas impurities and condensate. This affects and changes the maximum possible gas flowrate over time.

- In addition to being adjusted to the fuel CV, the air-fuel ratio needs to be adjusted according to the current operating conditions of the furnace [74].
- This study addresses this challenge by adopting and adapting existing air-fuel ratio determining methods for different operating conditions of the reheating furnace.

Novel contribution 2:

A unique and newly developed control philosophy for use by furnace operating personnel with less knowledge and expertise to make informed decisions for air-fuel ratio adjustments, instead of using the trial-and-error method.

- Literature studies [18], [34], [49]–[55], [79] focused on the management, optimal distribution and scheduling of by product gases to address their fluctuating supply challenges. However, the by-product gases also fluctuate in their CV. This results in combustion control challenges for the end-user due to the need to continually adjust the air-fuel ratio.
- In the events of drastic CV of COG fluctuations, which are common and frequent, operators override the furnace built-in control system and manually adjust the air-fuel ratio using a trial-and-error method. The adjustments need to be done for the individual furnace zones. The success of these adjustments depends, to a large extend, on the expertise and experience of the operator.
- Proper combustion air-fuel ratio is a critical factor for the efficiency of combustion processes. The use of over excessive or insufficient air during the trial-and-error adjustments cools down the furnace as the excess unburned fuel or air absorbs the available produced heat, while causing temperature instabilities. A cold furnace results in energy inefficiencies and production losses.
- An informed decision-making procedure for furnace operators is necessary.
- This work developed a new and unique control philosophy to address this challenge.

Novel contribution 3:

Development of a new generic and integrated producer-to-user solution approach to estimate the unknown calorific value of coke oven gas in integrated steel manufacturing facilities.

- Various fuel gas calorific value measuring equipment, typically in the form of gas analysers, are available on the market [4], [76]. However, the coke oven gas impurities have a tendency of clogging gas analysing equipment.
- Tools from literature [39] are available to estimate the unknown calorific value of coke oven gas. However, these methods give static values.
- Continuous reheating furnace operations require a time-continuous availability and reliable energy content quantification data of the gas [48], [74], [80], [81]. This allows for efficient and effective control of combustion processes.
- An integrated producer-to-user method is developed for reliable continuous-time estimation of coke oven gas calorific value.

Publication from the study

The presented thesis produced the following publication:

M. B. Mampuru, M. Kleingeld, J. H. Van Laar, J. H. Marais, and S. G. J. Van Niekerk, “Improving By-product Gas Utilisation in Steel Milling Operations,” *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2019. (In-press).

1.6 Thesis overview

Chapter 1

This chapter gives a background study on the current affairs pertaining to the iron and steel manufacturing industry, both on a global and local scale. The financial strain on the South African steel sector is discussed, leading to the introduction and discussion of improving and maximising the utilisation of by-product gases as alternative energy sources. The utilisation of coke oven gas in steel reheating furnace is given extended interest.

A literature review on the usage of by-product gases in reheating furnaces is conducted and the findings critically analysed. The findings led to the identification of the need for the study. The problem statement and the research objectives are outlined. The novel contributions of the study are discussed and summarised.

Chapter 2

This chapter provides and discusses the methodology developed for the solution towards the identified problem and meeting of the study objectives. The methodology is given in the form of solution steps outlined in chronological order. A new control philosophy is also developed to address the study problem. A method to quantify and evaluate the benefit of the solution is provided.

Chapter 3

Chapter 3 validates the developed methodology through an application on a case study. The validation follows the chronology as given in Chapter 2. The results are given and discussed.

Chapter 4

This final chapter concludes the study. The problem statement and study objectives are recalled and the requirement of being met is evaluated. A concluding discussion is given and recommendations for further work to expand on the studied field are given.

1.7 Conclusion

This introductory chapter gave a background on the global state of the iron and steel industry. Focus is then taken to the South African steel sector, discussing its challenges to remain financially afloat and competitive in the global market. Reducing energy and operational costs is focused on. The improvement and maximisation of by-product gas utilisation, particularly coke oven gas in steel reheating furnaces, are discussed and deliberated upon.

A literature study is conducted to identify and highlight the need of this study. The problem statement, research objectives and novel contributions of the study are included. A layout of the thesis which briefed contents of the various chapters of this document conclude this chapter. The next chapter discusses the developed methodology for the solution towards the identified problem and achieving the set objectives.

2 DEVELOPMENT OF METHODOLOGY

Electric arc furnace steelmaking [19]

[19] World Steel Association [BE], [Online] Available: steeluniversity.org. Accessed: 2019-03-08

2.1 Preamble

The background study given in Chapter 1 has emphasised the imperative need for the local steel industry to improve on their energy efficiency and reduce operational costs in order to remain globally competitive. By-product gases were shown to be compatible with high-temperature requirement applications, such as in steel reheating furnaces. Coke oven gas (COG) was also shown to be the most competitive with natural gas.

However, challenges associated with the utilisation of COG prohibit its maximum utilisation potential. The main challenges have been identified as fluctuating gas supply, varying composition, calorific value (CV) and the presence of heavy oils and tar, which affect the cleanliness of the gas. An unclean gas affects the availability, readability, accuracy and reliability of data from measuring equipment. Such occurrences adversely affect the combustion output and temperature control of the furnace.

In this chapter, a methodology for improving the utilisation of COG in steel reheating furnaces is developed and presented. The solution is complemented by a simplified tool to assist the furnace operators to manually implement air-fuel ratio adjustments in real-time when the need to override the built-in control system arises. Hence, a tool was developed for use by less knowledgeable and semi-skilled personnel in order to make sound decisions, instead of using trial-and-error, to keep the furnace temperature stable.

The solution development followed in this study was, as far as possible, based on day-to-day and real-world operational analysis, rather than on derivation from design principles [64]. This approach was considered to be sound and practical because it is not unusual for process and equipment operations to deviate from design specifications due to infrastructure aging and modifications over time [59]. A newly developed control philosophy will be outlined and discussed. A method to quantify the benefit of the solution will also be discussed.

2.2 Development of the methodology

2.2.1 Methodology development overview

The methodology development approach aimed at constructing a tool that is simple and generic. This is especially aimed at less knowledgeable and semi-skilled plant operators. This tool will be significant in the absence of the senior and expertly knowledgeable plant personnel, e.g. after-hours and during weekends.

A seven-step approach to the development of the methodology was followed. The solution ensured the use of the findings from the background and literature studies to satisfy the study objectives, as stipulated in Chapter 1. The methodology development procedure is illustrated in chronological order, using a flowchart in Figure 10. The steps are discussed in subsequent sections.

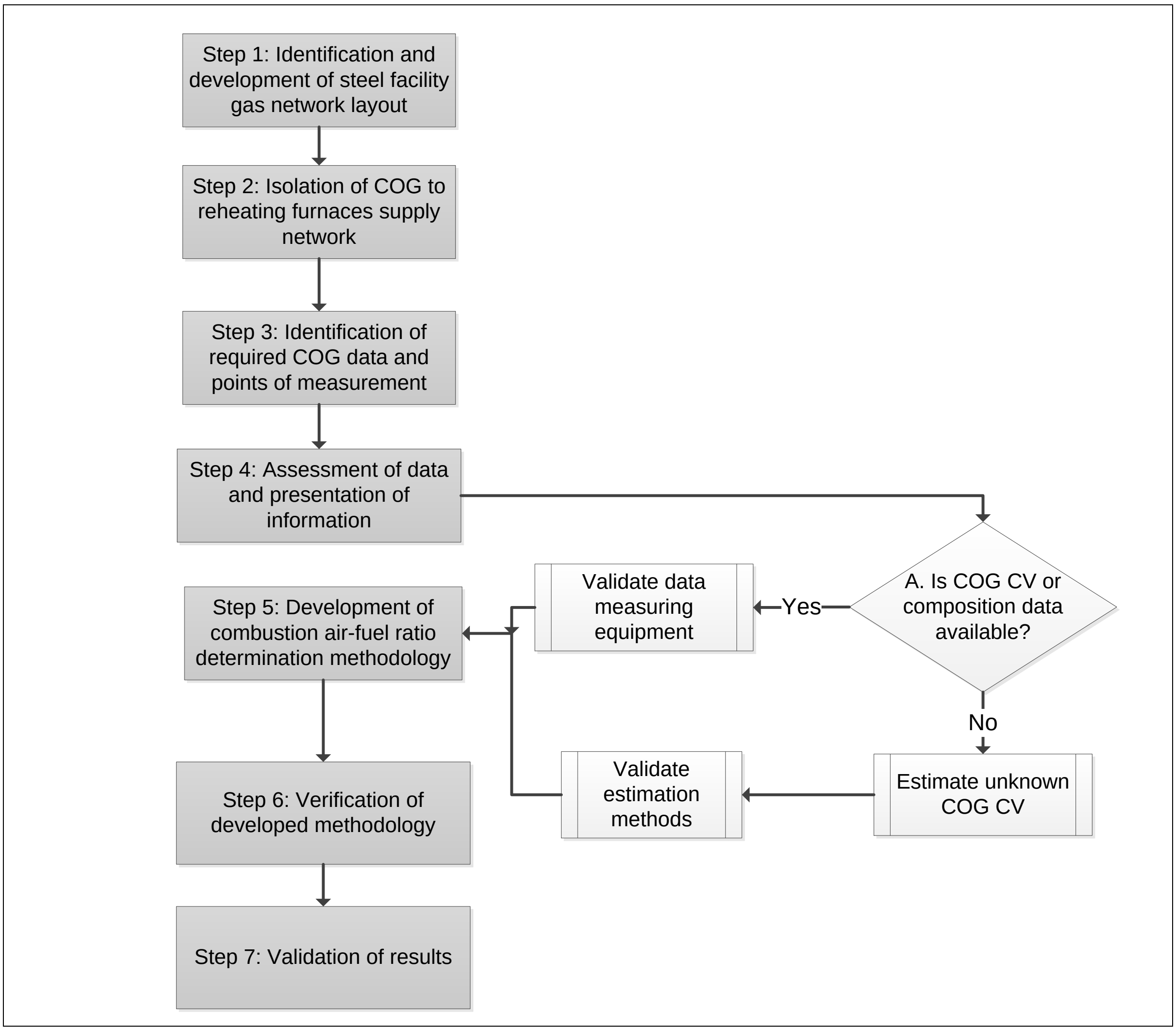

Figure 10: Methodology development overview

2.2.2 Step 1: Steel facility gas network layout

Steel manufacturing facilities are dynamic producers and consumers of various gases distributed through a network of interlinked pipelines. The first step in the solution approach is to do a thorough and complete investigation of the gas network. The by-product gas network can be subdivided into three main sections, i.e. the producers, storage and consumers. Typical by-product gas consumers are plants and boilers. Boilers produce steam for consumption and for electricity generation by alternators [9].

It was established in earlier sections that the gas network of steelworks is constituted by by-product gases, i.e. COG, BFG and BOFG, and natural gas, which is a purchased gas. The by-product gases are produced by their respective production process units and distributed to various consumers within the integrated steel facility. Each by-product gas has its own distribution network [34]. Figure 11 distinctly shows the by-product gas producers, storage and consumers, as well as a natural gas supply line.

Gas holders are critical components of the gas network. They serve as storage for surplus gas. In addition to being gas storage equipment, they, together with the boilers, serve as buffers for the system. They regulate and maintain safe operating pressure within the gas network [18]. Imbalances in by-product gas production and consumption are a frequent occurrence. These are due to unstable and unpredictable upstream and downstream process disturbances [30], [34], resulting in gas surpluses or deficits. Surplus gas is stored in gas holders. Fluctuations in gas holder levels indicate gas imbalances [31].

The by-product gas network also consists of flare stacks. These are used for relief when operating a high-pressure system and maintain safe operating levels [30]. Flaring is symptomatic of an energy inefficient fuel gas management system [32], [36]. A typical, overall steel facility gas distribution network is presented in Figure 11. A legend for identification of the various gas network configurations is presented in the figure.

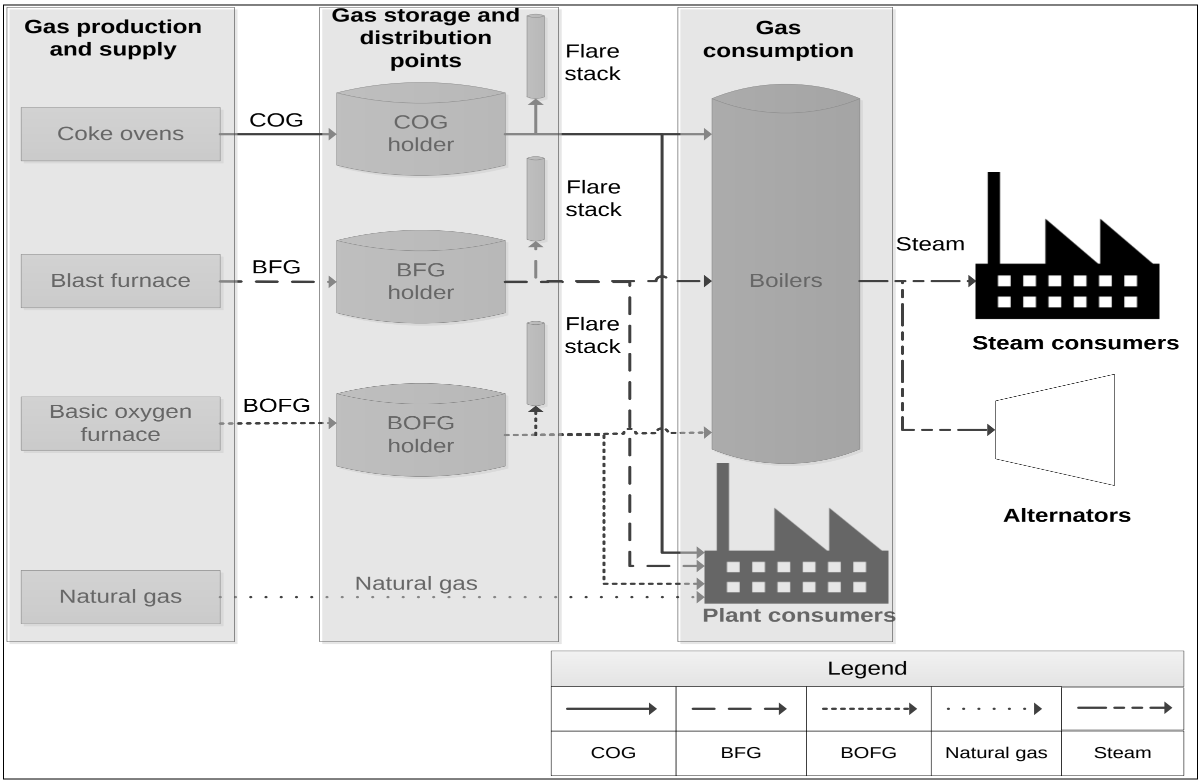

Figure 11: Gas distribution network on a steel manufacturing facility. Adapted from [34]

Upon identifying the components of the overall gas network, the process flow layout should be developed, studied and understood. The layout should clearly show how the various components are sequentially connected according to the identified process flow. The layout should be verified by experienced plant personnel prior to further commencement of any related and dependent applications.

2.2.3 Step 2: Coke oven gas to reheating furnaces supply network isolation

The next step is to isolate the coke oven gas to reheating furnaces supply network and acquire the layout. In the case where the layout is not readily available, it should be investigated and developed. This step allows one to identify what data is available and the respective measurement points. A typical COG to reheating furnaces network would comprise of the coke ovens, COG cleaning plant, COG holder and the reheating furnaces, as well as the flare stack. The isolated layout developed for this study is used as an illustrative example for this purpose, and it is represented in Figure 12. Different facilities will have unique configurations.

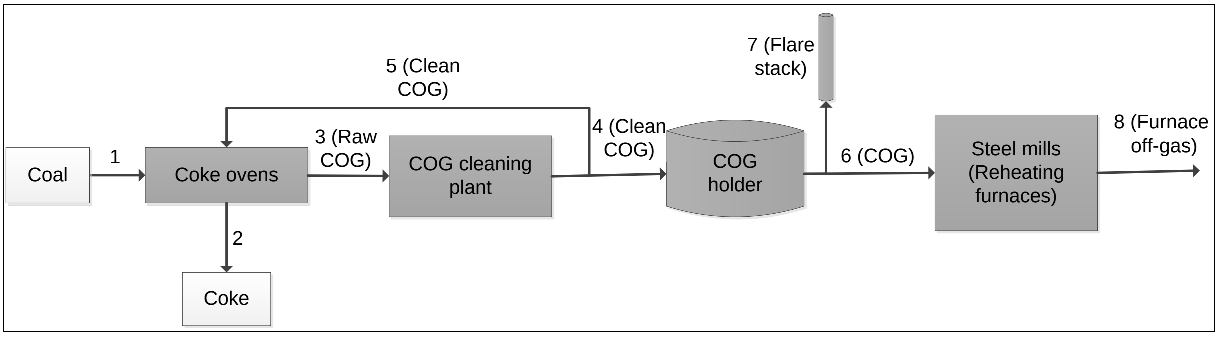

Figure 12: Coke oven gas to reheating furnaces network

In Figure 12, the input and output streams of the process units are presented. The coke ovens are fed coal (1) as the main raw material. The products of the coking process are shown as coke (2) and raw COG (3). The raw COG goes through a cleaning process at a by-product plant, the clean product of which is represented by (4). The COG cleaning plant produces other products such as tar and naphthalene. These were omitted from the presentation because they have an insignificant impact of the quality of COG.

In earlier sections it was indicated that the coke ovens also use COG as an energy source. This is represented by (5). Stream (4) feeds the COG holder, from which the reheating furnaces are fed (6). During COG surplus instances, the gas is released through the flare stack

(7) for safe operating pressure conditions maintenance. The furnace combustion off-gas stream is represented by (8).

2.2.4 Step 3: Identification of required COG data and points of measurement

The management, control and usage of fuel gases requires knowledge of their properties. Large scale steel facilities are equipped with gas analysing instruments installed at various points along the gas supply lines. Examples of such instruments are mass spectrometers and gas analysers. The next step will be identifying the points of measurement (PoM) and what data they provide. The outcomes should be presented on the layout, as exemplified in Figure 13. Different facilities will have unique configurations.

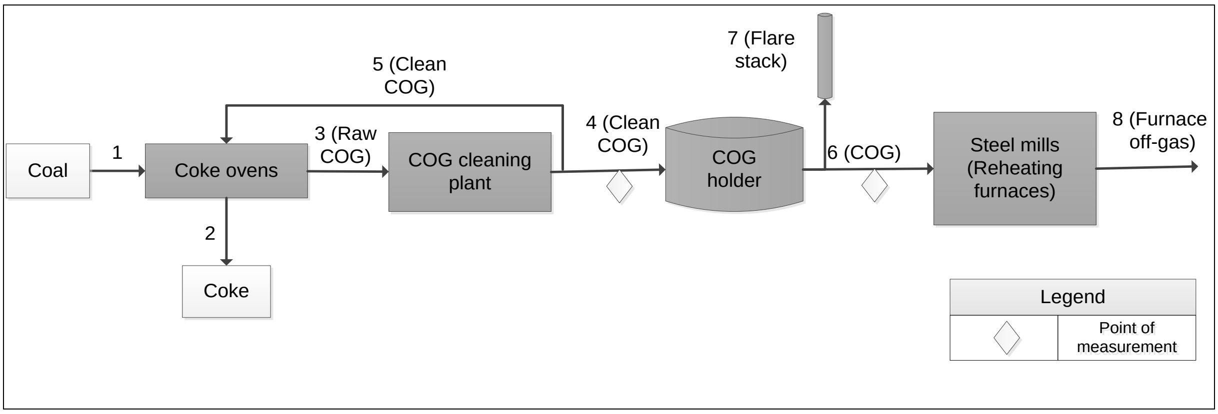

Figure 13: Points of measurement along COG to reheating furnaces supply line

Coke-making is a batch process. For steel plants with coke-producing facilities, the quality of the coke and COG indicate the performance of the coking process. While coke can only be analysed at the end of the process for product and process quality assessment, COG evolves throughout the duration of the process. For this reason, coke plants are typically equipped with gas analysers to acquire information on the instantaneous process performance from the exiting COG.

It is not feasible to place a gas analyser at (3) as the gas at the immediate exit point of the coke ovens is at high temperatures and still laden with dirt and heavy oils. Hence the PoM is rather located after the gas is cleaned, i.e. on stream (4), as illustrated in Figure 13. Another critical PoM for COG data is one on the feeding stream (6) to the reheating furnaces, also shown in Figure 13. Knowledge of the gas analysis at this point allows for proper management and control of the internal combustion processes of the furnace.

Gas-analysing instruments provide details on gas properties such as CV, composition, density, Wobbe Index (WI) [55], average molecular weight, etc. For the operation and control of combustion processes, the CV of the fuel gas is the most critical. The required fuel gas flowrate to the reheating furnace and the appropriate corresponding combustion air-fuel are mainly governed by this property.

The CV property is a measure of the energy content of a fuel. For a gas, this property is typically reported in units of energy per unit volume e.g. MJ/Nm^3 at 25 °C and 1 atm [9], [25]. The quality of the gas can also be indicated by its composition. The composition data indicate which elements and/or compounds are contained in the gas, and their respective concentrations. The gas component concentrations are expressed as a percentage. For a typical composition of COG, refer to Table 1, in Section 1.2.

2.2.5 Step 4: Data assessment and information presentation

The next step involves assessing, interpreting and presenting the information that the available data conveys. Presented in Figure 14 is an extension of Figure 13 for the purpose of illustrating the current step. This figure shows the identified data and the status of its availability. This has been represented with the use of the circular figures indicated on the various streams. The available data is denoted as “C” and “CV”, which indicate composition and calorific value, respectively.

Step 4 involves evaluating the question (A) in Figure 10, i.e. *Is CV of COG or composition data available?*. The following discussion of the solution development will first consider the case where the evaluation of the question (A) is given a “Yes” outcome, i.e. CV of COG or composition data is available from the PoMs.

Available CV of COG data

As per earlier presentation by Figure 13, the identified PoMs will measure data for streams (4) and (6). The outlet stream from the cleaning plants splits into (4) and (5). Because streams (4) and (5) split from the same COG cleaning plant outlet stream, they are assumed to have a similar C and CV. Therefore, information for stream (5) will be known. This assumption and consideration also hold true for streams (6) and (7). Details for stream (8) may be estimated from the assessment of the furnace reaction conditions or the off-gas property measurements.

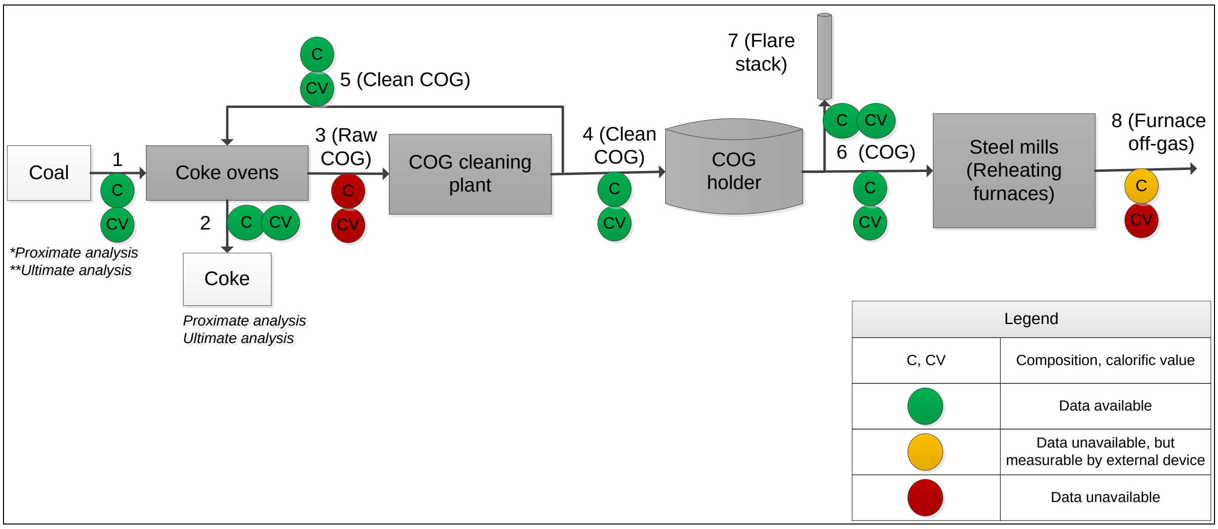

Figure 14: COG to reheating furnaces layout with gas properties and points of measurement

**Proximate analysis* indicates the ash, volatile matter, moisture and fixed carbon content in coal and coke [82].

***Ultimate analysis* indicates the carbon, hydrogen, oxygen and sulphur content of coal and coke [82].

Properties of COG and coke (2) are directly affected by the quality of the coking coal (1) used. The availability of data for streams (1), (2) and (5) allows one to estimate the data for stream (3). Laboratory reports from coal suppliers and/or on-site evaluation facilities provide the CV and composition information for coal and coke. The composition for coal and coke is expressed using proximate and ultimate analyses, as indicated in Figure 14.

The status of the data availability, or lack thereof, has been expressed using green, orange and red colouring, a method adopted from Campbell [82]. The green indicates that data is readily available, the orange indicates that the data is not readily available but can be measured using external devices, and the red is an indication that the data is not available. A legend detailing the data status is provided in the figure.

Validation of measuring equipment

The integrity and credibility of the measured data are critical if the data is to be considered reliable for energy quantification and usage by the facility. To ensure that the measured data meets these requirements, the measured data needs to be verified. This can be done by validating the measuring equipment by confirming up to date calibration compliance and the availability of accredited calibration certificates [83]. This mitigates the measurement uncertainty associated with measuring equipment [84], and gives external assurance for accurate CV measurements [81].

Unavailable CV of COG data

The discussion of the solution development up to this point was based on the condition that question (A) of Figure 10 is given a positive evaluation, i.e. a “Yes” outcome. However, it was discussed in Chapter 1 that one of the challenges users face with regards to utilising COG is the absence of gas analysis and energy content data. When this data is not available, question (A) of Figure 10 will have a negative evaluation, i.e. a “No” outcome.

Prior discussions have indicated that the COG goes through a gas cleaning process to remove impurities. These impurities are usually long-chain carbon compounds such as tar, naphthalene and heavy oils. However, improper plant maintenance results in insufficient removal of the impurities [58], with maximum cleaning efficiencies of 50 – 60 % [20]. These compounds condense within the gas stream at various stages of the gas flow network. The condensate builds up and ends up clogging injection nozzles of gas analysing equipment and the gas pipelines.

This entails that steel operations experience instances when they are without knowledge of the CV of the fuel gas the combustion processes are operating on. The lack of this knowledge leads to energy mismanagement. Energy measurement and quantification of fuel sources are essential for determining and improving the energy efficiency of steel operations [83]. Therefore, this study developed a methodology to estimate the unknown CV of COG. The methodology will be discussed in the next section.

Estimation of unknown calorific value of coke oven gas

The calorific value of the fuel is the most important quantifiable property for energy measurement and management in industrial applications [83]. It is also critical for the efficient control of combustion processes. For the purpose of this study, it is of utmost importance that the COG analysis data is available and known for the PoM within the closest proximity to the reheating furnace feed stream, i.e. stream (6), as per presentation in Figure 14. However, as it has already been emphasised, the analysis data may not always be available.

Integrated steel facilities are comprised of interlinked stages through which the products are sequentially processed from the raw materials to the refining phases. In this regard, the fuel gases are susceptible to property changes during transfer through the processing units, pipelines and storage in the system. The stages of COG handling have been described in earlier sections.

[20] Information received from interviews with plant personnel (Personnel requested that their identity remain undisclosed)

Using knowledge of the conditions of the process stages and equipment, the relationship of the CV of COG between any two or more points along the COG reticulation system can be modelled. This will allow estimation of the CV at one point using available data from another. The next session discusses three different methods for unknown CV of COG estimation.

Method 1: Estimation of unknown CV of COG – The coke-making process

Coke is produced through the thermal decomposition of coal in the absence of oxygen inside coke ovens at temperatures above 1 000 °C [85]. The quality of coal is expressed using CV, proximate and ultimate analyses. The proximate analysis expresses the composition of coal in terms of volatile matter, moisture, ash and fixed carbon [81]. Moisture combined with gases trapped within the coal structures constitute of the volatile matter. The volatile matter from the coke oven represents the raw COG.

The volatile matter components are gradually liberated from the coke ovens at different rates during the coal destruction process [85], [86]. The constituents and their properties are presented in Table 7. The vapourisation temperature represents the temperature at which the component becomes a gas and the heat of formation indicates the amount of energy required or released during the combustion of the various components.

Table 7: Volatile matter constituents and their properties [85], [87], [21]

Volatile matter constituents	Vapourising temperature (°C)	Heat of formation (kJ/mol)
Methane (CH_4)	-161.5	-74.85
Ethane (C_2H_6)	-88.6	-84.67
Hydrogen (H_2)	-252.79	0
Moisture (H_20)	100	-241.83
Carbon monoxide (CO)	-191.5	-110.52
Carbon dioxide (CO_2)	(sublimes at -78 °C)	-393.5
Ammonia (NH_3)	-33.43	-46.19
Hydrogen sulphide (H_2S)	-60.3	-19.96
Benzene + toluene + xylene (C_2H_6)	80.10	48.66
Tar ($C_{10}H_8$)	150	-

[21] United States Steel Corporation (USS), Crude coal tar Material Safety and Health Sheet (MSDS) [Online]. Available: ussteel.com. [Accessed: 2019-01-10].

Coke production is a batch process. Coals of different properties and qualities are usually blended in different ratios to achieve certain desired physical and chemical properties for the coke as determined by the coke plants and blast furnace personnel [85]. Determining the CV of COG using design principles and calculations (mass and energy balances) will prove to be a tedious task due to the coking process being associated with very complex conjugate flow and energy transport processes [85].

Instead, a simple and practical method approach will be taken for this study. The method considers the boundary as indicated in Figure 15. The approach involves analysing the present operating and behavioural state of the process and the actual data to develop the solution, as per emphasis by Swanepoel [64]. This is because the performance of the plants deviate from their design specifications due to aging and the modification of infrastructure [59].

As per a prior statement, the coking process is a batch process that is repeated and typically operated on a routine procedure. A predetermined coal blend is charged into the coke ovens at a specified time, then the coking reactions are allowed to take place for a given time duration, and finally the resulting coke gets discharged.

From the vapourisation temperatures shown in Table 7, it can be deduced that for the coking process, the volatile matter is released early in the process. The volatile matter has a significant impact on the CV of COG [39]. Further carbon cracking reactions release light hydrocarbon gases, which also contribute to the CV [85], [86].

This implies that one is able to study the CV of COG profiles with process time from various product cycles and develop a CV of COG curve using actual measured available data. It must be ensured that the coal blend and production time parameters remain constant. In the event of any deviations, revision of the curve will be required.

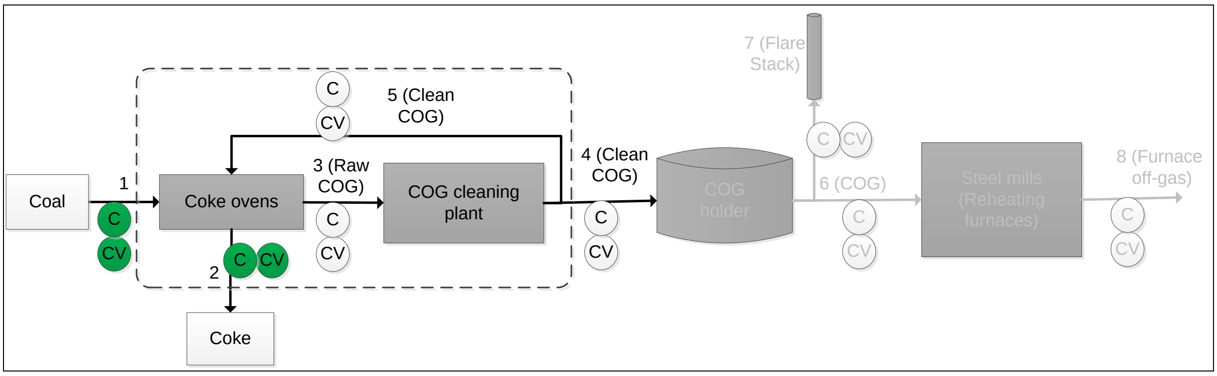

Figure 15: Estimation of unknown CV of COG – The coke-making process

Possible causes of deviations from a given developed curve may include:

- Changes in coal blends;

- Production delays;
- Newly maintenance of the coke ovens; and
- Different weather conditions due to air leakage effects.

Method 2: Estimation of unknown CV of COG - Gas storage buffers

It has been stated in Chapter 1 that the CV of COG measured at any one point fluctuates over any given time period. The CV of COG is affected by the coal type used in the coke ovens, the coke production stage and the efficiency of the cleaning plant; among other factors. This implies that gas samples produced and received by the storage buffer at different times will not have similar properties.

Gas storage buffers in large scale production facilities create a delay in the consumption of the gas between the point of gas availability from the source and when it is received by the plant consumers [83]. The delay introduces the effect of residence time (τ) which is expressed by equation (1) [64].

$$\tau = \frac{V_{Buffer,t-\tau}}{\int_{t-\tau}^{t} \dot{V}_{COG}\, dt} \tag{1}$$

Where:

τ:	Residence time in buffer (hr);
$V_{Buffer,t-\tau}$:	The volume of the buffer at time $t-\tau$ (m^3);
t:	Analysis time indicator (hr); and
$\dot{V}_{COG}$:	Volumetric flowrate of COG (m^3/hr).

Figure 16 presents a demonstrative diagram to reference when evaluating the change in COG properties during passage through a storage buffer.

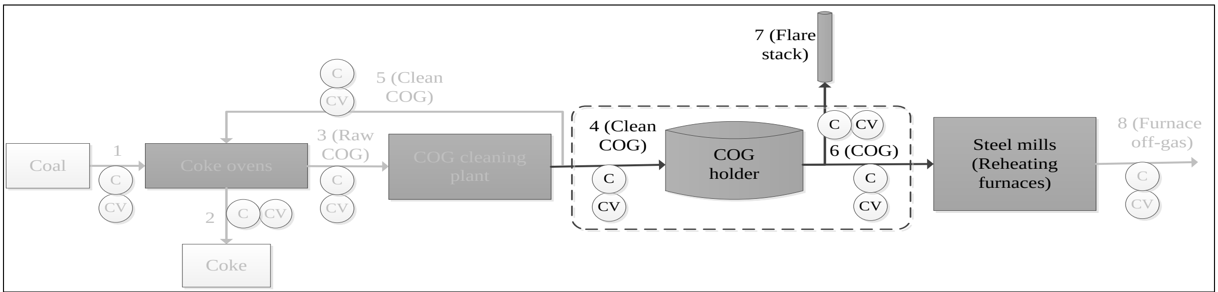

Figure 16: Estimation of unknown CV of COG: Gas storage buffer

The COG holder receives, stores and transfers the gas at varying rates depending on the overall facility gas production and consumption rate. Due to the high entropy of gaseous matter, it is assumed that the gas mixture in the buffer will become homogenised. Therefore, the COG holder will influence the CV of the gas by introducing the buffer effect, i.e. homogenisation.

With homogenisation, an equal distribution of the gas properties across the volume of the buffer is assumed [64]. This subjects the gas to CV changes between the points of buffer inflow and outflow. Therefore, with reference to Figure 16, it is expected that stream (4) CV ≠ stream (6+7) CV. However, the CV of the gas mixture inside the buffer is equal to the CV of the gas extracted from the buffer, i.e. stream (6+7) as per Figure 16. The concept of homogenisation is illustrated by Figure 17.

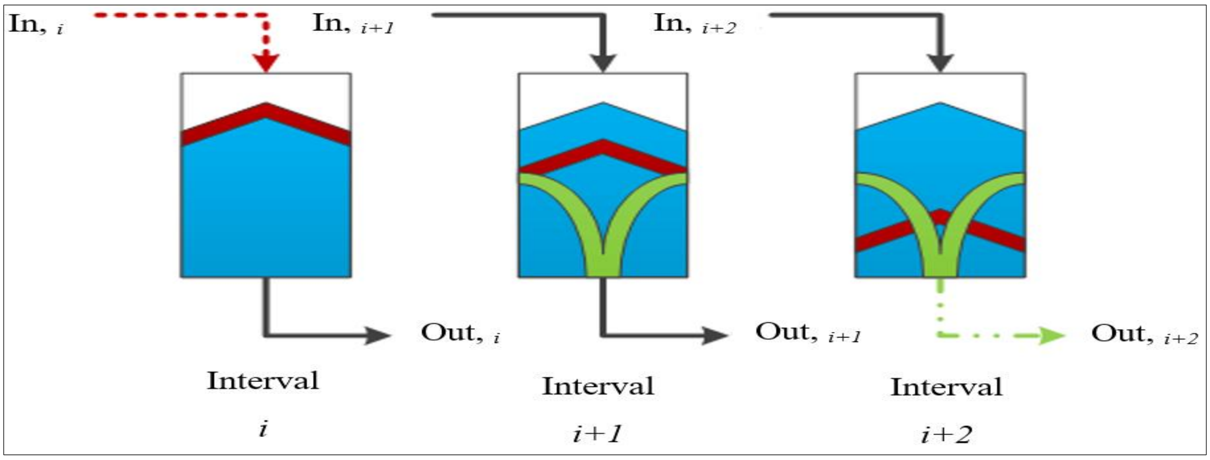

Figure 17: Homogenisation buffer extraction pattern. Taken from [83]

The CV of COG with a storage buffer can be determined by [64]:

$$CV_{COG,Out,t} = CV_{COG,Buffer,t} = \frac{V_{Buffer,t-\tau} * CV_{COG,Buffer,t-\tau}}{V_{Buffer,t-\tau} + V_{COG,In}} + \frac{V_{COG,In} * CV_{COG,In,t-\tau}}{V_{Buffer,t-\tau} + V_{COG,In}} \tag{2}$$

Where:

$CV_{COG,Out,t}$: Calorific value of COG at outlet of buffer at time t (MJ/Nm^3);

$CV_{COG,Buffer,t}$: Calorific value of COG inside the buffer at time t (MJ/Nm^3);

$V_{Buffer,t-\tau}$: The volume of the buffer at time $t-\tau$ (Nm^3);

$CV_{COG,In,t}$: Calorific value of COG at inlet of buffer at time $t-\tau$ (MJ/Nm^3);

$CV_{COG,Buffer,t-\tau}$: Calorific value of COG inside the buffer at time $t-\tau$ (MJ/Nm^3); and

$V_{COG,In}$: Inflow volume of COG (Nm^3).

For a representative estimation method, the sample size is a critical factor. The minimum required number of samples needs to be known and complied to. Van Aarde [81] used Green's method as a test for the representation of a sampling method in data modelling practices. The method uses the number of variables upon which the estimated or predicted value depends. This test method will be used for the sample size determination for the purpose of CV of COG estimations with the buffer. The test equation is expressed thus [81]:

$$p = 50 + 8\,(q) \tag{3}$$

Where:

p: Sample size; and

q: Number of predictors

Method 3: Estimation of unknown CV of COG - Products of combustion

The analysis of the products of combustion provides information on the materials and energy use and efficiency of the reheating furnace. By evaluating the enthalpy of all the products of combustion at the pre-combustion temperature, while condensing any vapour produced, the calorific value of the combusted fuel can be determined [25]. Figure 18 shows a schematic diagram showing the boundary for unknown CV of COG estimation using the products of combustion. The CV of COG can be determined as the enthalpy of combustion, i.e. the energy released during the combustion of the gas.

Some plants are equipped with off-gas analysing equipment for the purpose of furnace performance evaluation. The decision to install or retrofit a plant with off-gas analysers is sound and feasible when combusting clean fuel gases. However, as it has already been emphasised, COG cannot be considered a clean fuel gas. The off-gas from furnaces combusting COG have a high tendency to clog gas analysers due to less than optimum combustion process efficiencies [22].

[22] Information received from interviews with plant personnel (Personnel requested that their identity remain undisclosed)

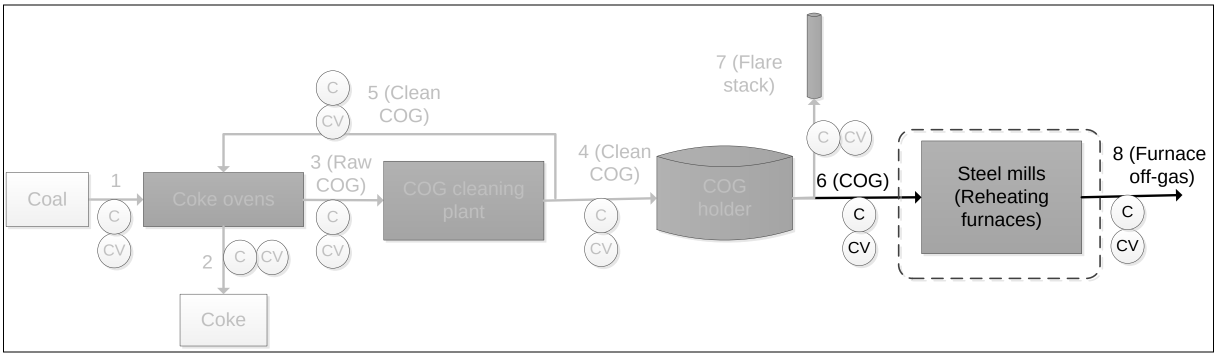

Figure 18: Estimation of unknown CV of COG: Products of combustion

In this study, the furnace off-gas readings were manually taken using a mobile gas analyser. The materials and instruments are enlisted; and methodology followed is described below:

Materials and instruments

- Telegan Tempest 100 V3.0 off-gas analyser;
- 1-meter coiled copper rod;
- 2-meter stainless-steel rod; and
- 12 litre bucket filled with ice-water.

Furnace off-gas analysing methodology

A Telegan Tempest 100 V3.0 mobile off-gas analyser was used for the described task. Assurance was made that all the zones of the furnace were combusting COG for the analysis of the products of combustion of the gas. With the assistance of plant personnel, an appropriate and safe PoM was located on top of the furnace. Assurance was also made that the PoM on the off-gas exit tunnel was before the point of dilution air injection.

For the gas analysis, the analyser was connected to one end of the copper coil, with the other end connected to the stainless-steel rod. The stainless-steel rod was inserted down into the furnace off-gas ejection channel. The copper coil was submerged into the ice-water bucket for gas cooling. Gas readings were taken at 5-minute intervals for the duration of the measurements. This was to ensure that enough readings with precise data were taken for the evaluation.

To estimate the CV, equation (4) [87] is applied:

$$CV = H^{\circ}_{C,(25\,^{\circ}C,1\,atm)} = \Sigma H^{\circ}_{f,(25\,^{\circ}C,1atm)}(Reactants) - \Sigma H^{\circ}_{f,(25\,^{\circ}C,1atm)}(Products) \quad (4)$$

Where:

CV:	Calorific value of COG (MJ/Nm^3);
$H^{\circ}_{C,(25\,^{\circ}C,1\,atm)}$:	Enthalpy of combustion (MJ/Nm^3) at 25 °C and 1 atm;
$\Sigma H^{\circ}_{f,(25\,^{\circ}C,1atm)}(Reactants)$:	Sum of enthalpy of formation of the reactants at 25 °C and 1 atm; and
$\Sigma H^{\circ}_{f,(25\,^{\circ}C,1atm)}(Products)$:	Sum of enthalpy of formation of the products at 25 °C and 1 atm.

Validation of calorific value estimation methods

The purpose of the estimated data validation step is to demonstrate actual data characteristics representation and to ensure authentic behaviour reproduction [81]. Van Aarde [81] discusses two statistical parameters which present a quantitative measure of validation for estimation methods, namely the mean absolute error (MAE) and the comparison coefficient (CC) [81]. A detailed completion of steps 3 and 4 allows one to make sound decisions on how to undertake the following step, which is the determination of the combustion air-fuel ratio.

2.2.6 Step 5: Developing the air-fuel ratio determination methodology

The maximum release of energy from a fuel depends on the efficiency of the combustion process. A critical factor to this efficiency is the appropriate air-fuel ratio. Once information about the CV and/or composition of COG is known, one can proceed to determine the required air-fuel ratio. The air-fuel ratio is mainly a function of the CV of the fuel, even though other factors such as the chemical composition and burner efficiency play a role in the ultimate value.

The first step is to evaluate the thermal energy flows of the reheating furnace. This requires one to identify the energy inputs and outputs of the system. The energy input mainly comes from the fuel, for which, depending on design and availability, may be liquid and gaseous [57]. Some reheating furnaces may have installed combustion air pre-heating equipment. The combustion air is preheated through heat exchange with the furnace off-gas. This offers additional input energy in the form of combustion air sensible heat.

The energy output of the furnace is comprised of the heat absorbed by the heated steel products and the off-gas. Energy also exits the furnace by heat losses through openings, heat absorption by furnace walls and skids, among other factors. Shown in Figure 19 is a simplified representation of the thermal flows of a reheating furnace equipped with a recuperator. The descriptions of the terms are given in subsequent calculations steps.

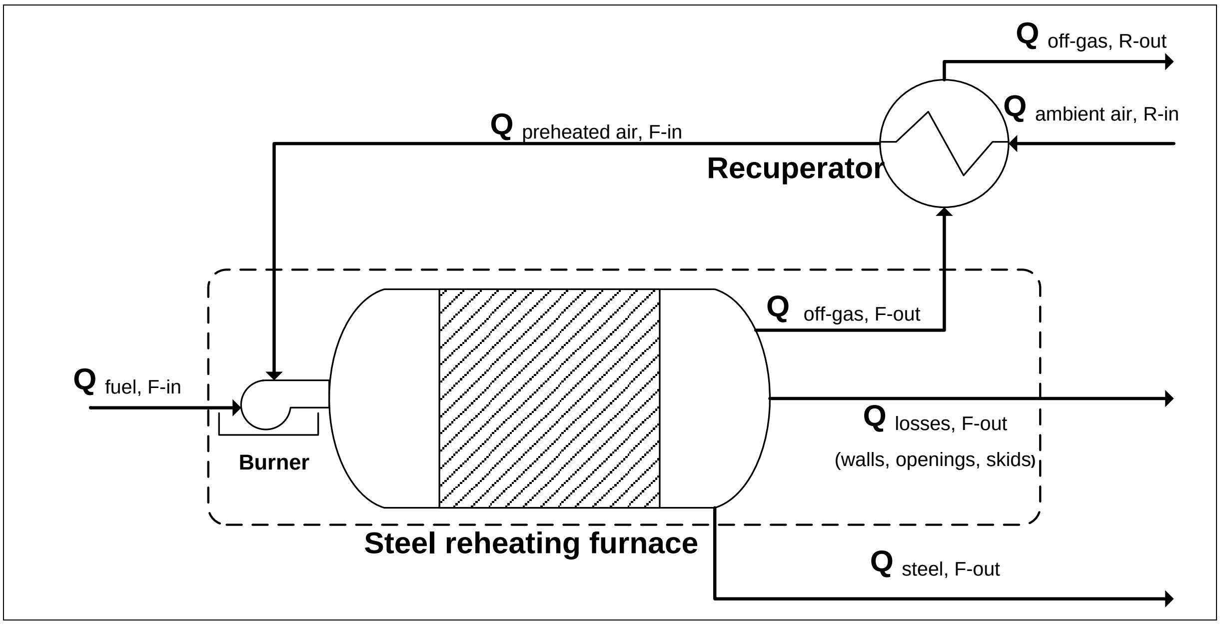

Figure 19: Thermal energy flows in a steel reheating furnace. Taken from [76]

The recuperator is a heat exchanger, which transfers heat from the furnace off-gas to the incoming combustion air. This is to elevate the air temperature from ambient and improve the energy efficiency of the furnace. A thorough evaluation of the thermal energy flows allows one to determine the energy input requirements of the furnace.

Thermal energy flows evaluation

To determine the energy input requirements of the furnace, a thermal energy balance needs to be performed. Considering the reheating furnace represented in Figure 19 and the indicated boundary, the heat balance is presented thus [67]:

$$Q_{fuel,F-in} = Q_{steel,F-out} + Q_{losses,F-out} + Q_{off-gas,F-out} - Q_{preheated\ air,F-in} \quad (5)$$

Where:

$Q_{fuel,F-in}$:	Heat energy input from the fuel into the furnace (MJ/hr);
$Q_{steel,F-out}$:	Heat absorbed by steel products exiting furnace (MJ/hr);
$Q_{losses,F-out}$:	Heat losses from the furnace (MJ/hr);
$Q_{off-gas,F-out}$:	Heat losses due to furnace off-gas (MJ/hr); and
$Q_{preheated\ air,F-in}$:	Sensible heat of preheated combustion air (MJ/hr).

With:

$$Q_{preheated\ air,F-in} = Q_{ambient\ air,R-in} + Q_{off-gas,F-out} + Q_{off-gas,R-out} \quad (6)$$

Where:

$Q_{ambient\ air,R-in}$:	Sensible heat of ambient air into the recuperator (MJ/hr); and
$Q_{off-gas,R-out}$:	Heat losses due to recuperator off-gas (MJ/hr).

The furnace energy input requirement factor, i.e. $Q_{fuel,F-in}$ can then be determined by evaluating the individual Q terms in equation (5). Let n be any component that participates in the heat balance and appears on the left side of equation (5). The term Q_n for component n with mass m_n is then determined by equation (7), as such:

$$Q_n = m_n \int_{T_n,F-in}^{T_{n,F-out}} C_{p_n}(T)\, dT \quad (7)$$

Where:

Q_n:	Heat absorbed by component n (MJ/hr);
m_n:	Mass of component n (T);
$C_{p_n}(T)$:	Temperature dependent specific heat capacity of n (kJ/mol °C); and
$T_n, F-in$, $T_n, F-out$:	Furnace inlet and outlet temperatures for n, respectively (°C).

The total sum of these Q terms in equation (5) will give the required furnace energy input from the fuel. The next step will be the determination of the amount of fuel that will provide the required heat energy. For this, equation (8) will be applied thus:

$$Q_{fuel,F-in} = \dot{V}_{fuel,F-in} \times CV_{fuel,F-in} \quad (8)$$

Where:

$\dot{V}_{fuel,F-in}$: Required amount of fuel (m^3/hr); and

$CV_{fuel,F-in}$: Calorific value of fuel (MJ/Nm^3).

At this point, $Q_{fuel,F-in}$ and $CV_{fuel,F-in}$ are known, hence one can solve equation (8) for the required fuel amount, i.e. $\dot{V}_{fuel,F-in}$. Once the amount of required fuel has been established, the next step is to determine the appropriate combustion air. This will be achieved by performing reactive mass balances.

Reactive mass balances

The release of the energy content of a fuel occurs when oxygen in air reacts with the combustible components of the fuel. The amount of air required to fully combust 1-unit mass of fuel will be determined by applying reactive mass balances. For the mass balance calculations, the following assumptions are taken into account [66], [87]:

- Reactive components of the fuel will only react with oxygen and not with other present species.
- The fuel gets fully combusted in the reaction chamber i.e. all carbon, hydrogen and sulphur components get oxidised to CO_2, water (H_2O) and SO_2, respectively, in the presence of excess oxygen.
- No dissociation of the products of combustion. For example, at temperature conditions of 1 atm and 1 227 °C, CO_2 has a 0 % dissociation. However, when the temperature increases to 2 227 °C, a 2,2 % dissociation is experienced. The dissociation is into CO and O_2. Therefore, the impact of these possible dissociation reactions will be considered as negligible and disregarded in the subsequent calculations [66].
- Combustion air is composed solely of O_2 and N_2. The presence of other ambient air constituents is neglected.
- Nitrogen is an inert gas and, therefore, does not participate in the reactions.

An example of the composition of COG is shown in Table 8. Using this composition, one can identify the various elements present in the COG and use these for the fuel representation when performing the reactive mass balance calculations, as shown by the first term on the left side of equation (9). Different COG samples from different facilities will have unique compositions at any given time.

Table 8: An example of coke oven gas constituents and composition

Component	CH_4	CO	CO_2	H_2	N_2	O_2	C_2H_4	C_2H_6	C_3H_8	H_2S
Concentration (vol %)	21.63	7.48	2.39	53.14	11.16	1.44	0.42	2.18	0.09	0.07

Considering the aforementioned assumptions, the reactive mass balance equation is represented thus [66]:

$$C_aH_bO_cN_dS_e + u_0O_2 + 3.76u_0N_2 \rightarrow wCO_2 + xH_2O + ySO_2 + zN_2 \quad (9)$$

Where:

$C_aH_bO_cN_dS_e$: The fuel representation (COG);

$u_0O_2 + 3.76u_0N_2$: Expression of the combustion air component (21% O_2 and 79% N_2);

CO_2, H_2O, SO_2, N_2: Products of combustion;

w, x, y, z: Stoichiometric coefficient of chemical species; and

a, b, c, d, e: Chemical species subscripts.

Once the mass balance participating species are known and presented, and using the composition given in Table 8, individual component balances from both sides of equation (9) can be performed as such [66]:

Carbon balance (C)

$$a = w = \%CH_4 + \%CO + \%CO_2 + (2 \times \%C_2H_4) + (2 \times \%C_2H_6) + (3 \times \%C_3H_8) \quad (10)$$

Hydrogen balance (H)

$$b = 2x = (4 \times \%CH_4) + (2 \times \%H_2) + (4 \times \%C_2H_4) + (6 \times \%C_2H_6) + (8 \times \%C_3H_8) + (2 \times \%H_2S) \quad (11)$$

Nitrogen balance (N)

$$d = 2 \times \%N_2 \quad (12)$$

$$z = (3.76 \times u_0) + 0.5d \quad (13)$$

Sulphur balance (S)

$$e = y = \%S \quad (14)$$

Oxygen balance (O_2)

$$c = (0.5 \times \%CO) + \%CO_2 + (0.5 \times \%H_2O) + \%O_2 \quad (15)$$

$$u_0 = \mathrm{w} + (0.5 \times x) + \mathrm{y} - \mathrm{c} \quad (16)$$

The completion of this step allows one to obtain the stoichiometric (theoretic) combustion oxygen amount, from which the stoichiometric air, and thereafter the air-fuel ratio, can be derived by applying equation (17).

$$\%\, oxygen = \frac{amount\ oxygen}{amount\ air} \times 100 \quad (17)$$

In large scale reaction chambers, such as reheating furnaces, where perfect mixing of the reagents participating in the reactions is rarely achieved nor controlled, the use of stoichiometric air-fuel ratio leads to inefficient fuel consumption. For a complete and efficient combustion process, the use of excess air is necessary. Excess air increases the conversion of the fuel for maximum energy release. Therefore, to supply stoichiometric oxygen proportions to the fuel, combustion reactions always use more air than is needed [87].

However, the excess air still needs to be fed in accordance to the reheating furnace operational capacity and characteristics. As it was established earlier, a reheating furnace is compartmentalised into zones. In that regard, a generic furnace air-fuel ratio will not be an effective solution because the furnace temperature zones exhibit different and unique combustion characteristics. The local air-fuel ratio appropriate for the individual zones will, therefore, be most relevant.

Typically, reheating furnaces take readings and keep records of fuel gas and air data fed to the burners in the various zones. The air measurements represent the actual air consumption data by the zones, which is significant as this reflects the operating conditions of the zone at any given time. Hence, it is important to take the actual air into consideration.

The relationship between the excess and actual air is expressed by the excess air coefficient (α). It is ideal to establish α for the respective reheating furnace zones. Therefore, for any furnace zone i, the excess air coefficient can be determined thus:

$$Excess\ air\ coefficient\ (\alpha_{zone\ i}) = \frac{amount\ air_{(actual_{zone\ i})}}{amount\ air_{(stoichiometric)}} \tag{18}$$

2.2.7 Step 6: Verification of methodology

The methodology will be verified by simulating the effects that the changes in CV of COG and the corresponding air-fuel ratio have on the furnace temperature. This is done for testing the feasibility of the solution on the system and for the identification of its impact before practical implementation. The CV of the fuel and the combustion air-fuel ratio have a direct impact on the furnace temperature output. To study the effect of the CV and air-fuel ratio on the temperature, the concept of adiabatic flame temperature will be applied for the simulation model.

Adiabatic flame temperature (T_{ad}) is the highest attainable temperature from the release of the energy content of a fuel when combusted [87]. Using the caloric value of COG and the heat capacities of the products of combustions, the T_{ad} can be determined by applying equation (19):

$$CV = \int_{T_{initial}}^{T_{ad}} [\sum_i C_{P_i}]\, dT \tag{19}$$

Where:

T_{ad}: Adiabatic flame temperature (°C);

$T_{initial}$: Pre-combustion temperature (°C); and

C_{P_i}: Heat capacity of products of combustion species (kJ/kmol °C).

Furnaces are non-insulated reaction chambers, therefore, heat transfer and losses from the products of combustion occurs. The furnace temperature is measured using thermocouples. They measure the local furnace atmosphere temperature and not the flame temperature. The deviations from the measured temperature and the calculated T_{ad} will be evaluated and accounted for in the temperature effect simulation studies.

The results of the simulations will be compared to actual data for verification. An acceptable accuracy between the simulated results and the actual data will confirm the developed methodology as valid. The method will then be practically applied on a case study for the validation of the study results. The validation step is discussed in the next section.

2.2.8 Step 7: Validation of results

The final step involves validating the results of the study. This will be done by the practical application of the developed solution methodology to a case study. For this purpose, pilot studies on a billet mill reheating furnace will be conducted. For the validation studies, the developed model will be used to determine the combustion air-fuel ratio according to the CV of COG. The temperature responses to the incoming CV of COG and air-fuel ratio of the various furnace zones will be observed, with focus on the temperature stability.

The energy savings and corresponding financial benefit of the strategy for the present study will be quantified using a baseline model developed and to be presented in Section 2.4. The energy and cost benefits will be determined based on lost saving opportunities using furnace historic data. The average natural gas maximum price for the specific period will be used for the financial benefit determination.

2.3 A newly developed control philosophy

An objective of this study is to develop a simple tool for use by plant operators to make informed decisions when controlling the combustion process of COG in the furnace. This especially for when the need arises to override the built-in control system during challenges of poor furnace performance due to poor COG quality and fluctuations. Control rooms will typically have installed several electronic graphic displays for monitoring and visualising the performance trends of various processes of the plant. Examples includes trends for process variables such as level, pH, pressure, flowrate, temperature and fuel gas CV.

An important process variable for the steel reheating furnaces is the temperature of the zones. It has been stated that the optimum temperature up to which the steel stock needs to be elevated to prior to rolling is in excess of 1 250 °C. Lower than optimum temperatures increases the required rolling power and increases the probability of having rejects due to the inability of the steel to reach the desired metallurgical properties [88].

At less than optimum temperature conditions, the furnace becomes cold. To prevent a “cold furnace” from occurring, a new control philosophy has been developed as a tool for plant operators to assist in adjusting the air-fuel ratio when the need for manual interventions arises. This task has been achieved using a trial-and-error method.

The furnace operators need to always keep close attention to the temperature trends of the furnaces and be aware if the temperature has been consistently on a decline until reaching temperatures of 1 100 °C and below. If this is the case, other operational disturbances that would potentially affect the temperature should be taken into account and evaluated before being disregarded as possible causes. Operational disturbances such as furnace idling, maintenance procedures, steel profile changes and reduced gas pressure have the effect of furnace internal temperature reduction.

Once other operational disturbances have been ruled out, it should be confirmed that the fuel gas being combusted in the furnace is COG. Under ideal and normal operating conditions, the system will input more fuel gas to the zone burners whenever the furnace temperature drops. The fuel gas feed flowrate to the furnace zones will be increased until the required temperature is reached. The gas will similarly be cut back when the set temperatures are reached [9].

However, the system does not always operate ideally and require human manual interventions. If CV data for the COG is available, one should observe the data trend for any sudden changes, and more especially, if the CV has been declining consistently. Otherwise, if CV data is not available, the applicable method developed in this study should be applied to estimate the unknown CV. With knowledge of the CV, the appropriate gas and air flowrate can be adjusted.

The gas flowrate adjustments must be followed by the relevant air-fuel ratio settings until the furnace temperature reaches stability. If the gas CV is so low that it will require more than burner design specification flowrates to reach temperatures, the gas combusted in the furnace zones must be switched to natural gas. The natural gas feed must be kept until the temperature becomes stable again and/or the CV of the COG recovers, then switch back to COG. The developed control philosophy is presented in Figure 20.

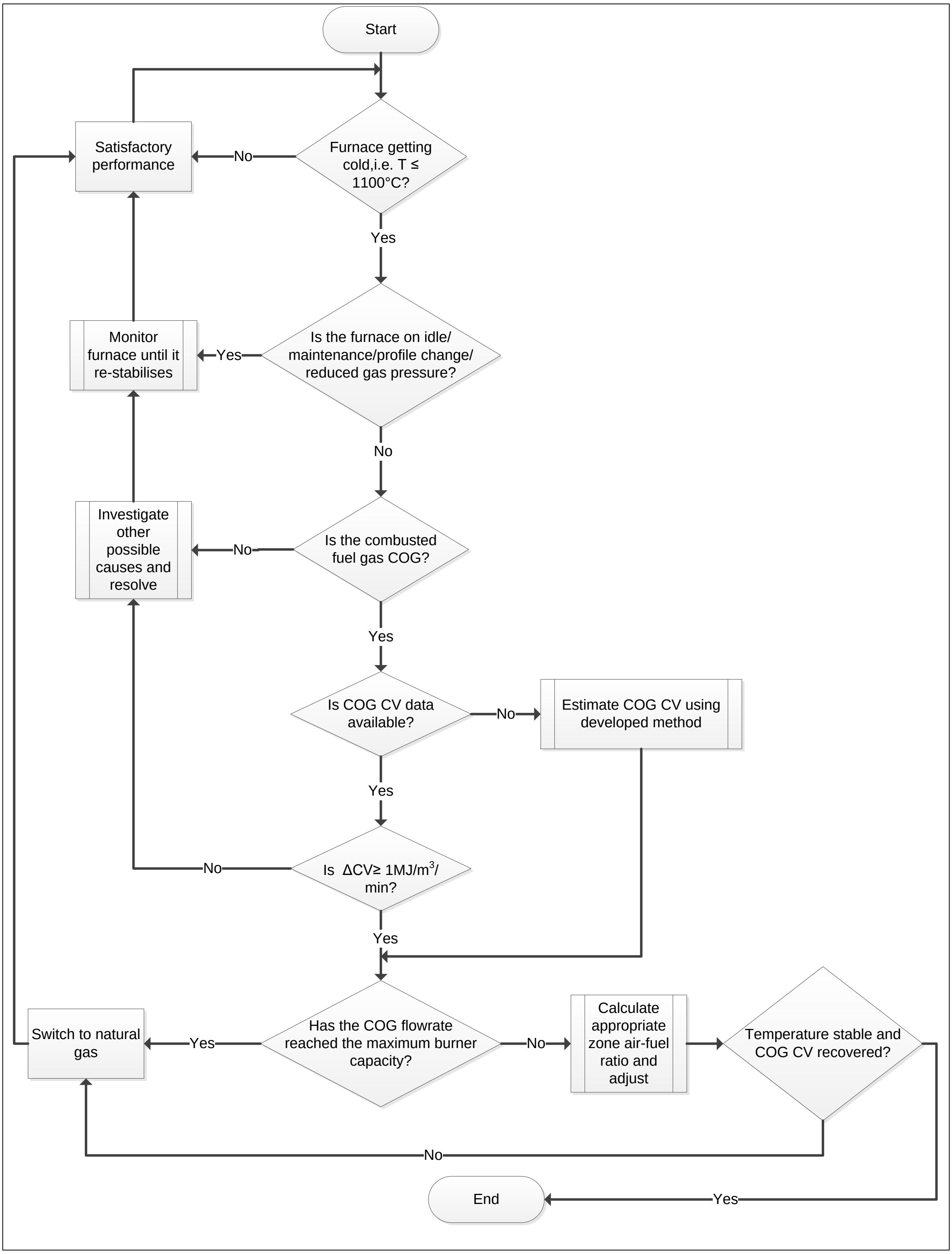

Figure 20: A newly developed reheating furnace control philosophy

2.4 Quantification of benefit methodology

2.4.1 Baseline development

The developed study solution intends to increase the consumption of COG by the reheating furnaces while reducing natural gas consumption. This is due to natural gas being significantly more expensive to use than COG as it is outsourced from third-party suppliers, whereas COG is readily available within the premises of integrated steel facilities. The method for quantifying the impact of the solution will, therefore, need to be determined and validated prior to the solution implementation.

To quantify the solution impact, the energy usage and performance of the furnace needs to be characterised and evaluated over a pre-determined period prior to the intervention. This will require historic energy usage data of the furnace over the determined period. The selected period should be reflective of a majority of the possible furnace operational configurations [9]. Using the historic data, a baseline can be developed.

A baseline is a measure of the energy consumption of the system in the absence of energy saving interventions [9], [89]. The energy consumption of the furnace is influenced by several factors, namely type of combustion fuel, maintenance delays, production planning, furnace operating conditions, heat losses, production rates and steel profiles. Steel profiles differ in size, shape, grade and charge temperature, among other factors.

Historic energy consumption data for the furnace is necessary to develop the baseline. For this study, natural gas and COG consumption data will be used. Historic data from the defined baseline period should be used to ensure reliability. Although the energy consumption is generally a function of several factors, there are certain parameters that are considered as energy drivers. These energy drivers should be known, measurable and verifiable. They should remain consistent through the baseline measurement period and post implementation [89].

It is crucial to use a high-quality dataset for the baseline development for a reliable model. Hence the historic data will require a quality evaluation process. For an all-inclusive and system reflective baseline, the data used should satisfy the following requirements [89]:

- A full operating cycle for the measurement period,
- All operating conditions must be represented,
- Data must be complete, and
- Data must be most recent (prior to implementation).

Baseline data quality evaluation

It has been indicated that the use of measuring equipment subjects data to errors and uncertainty [84]. A high quality of data used in modelling applications is critical. Erroneous data has adverse effects on the model reliability, accuracy and true reflection of operational conditions. Therefore, the process of data evaluation and "cleaning" is necessary. Booysen [90] developed a methodology to evaluate and qualify datasets, presented in Figure 21.

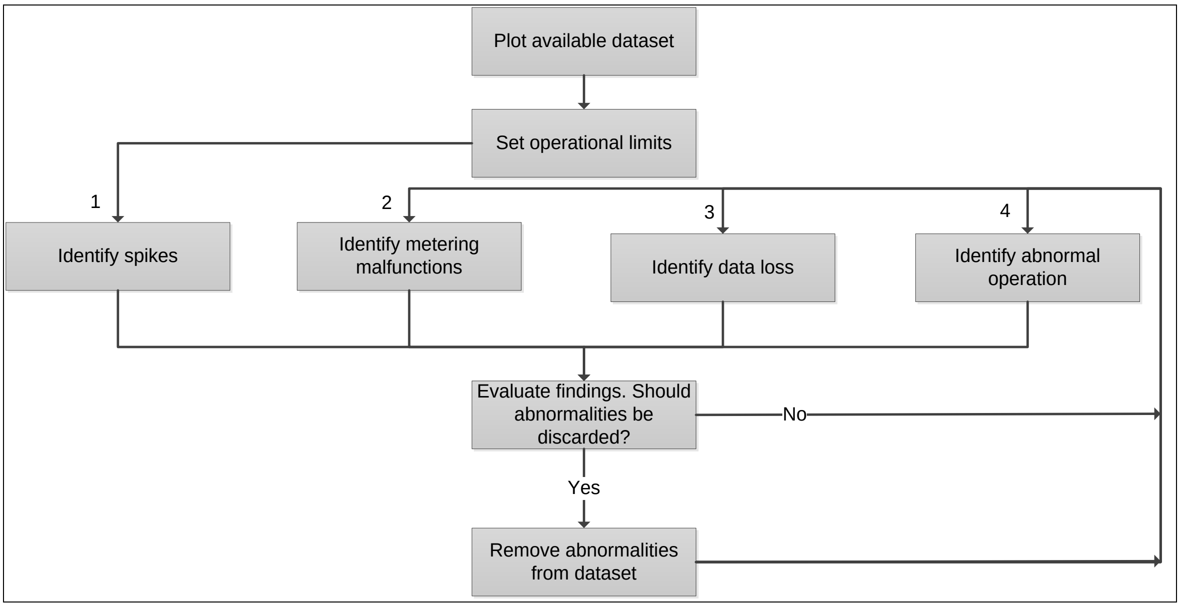

Figure 21: Methodology for dataset quality evaluation. Taken from [90]

According to the methodology, plotting the data and setting the minimum and maximum operational limits enables one to evaluate the data. The evaluation procedure is classified into four steps. Steps 1-3, i.e. spikes, metering malfunctions and data loss identifications, respectively, identify abnormal measurements. Abnormal system operations are identified by Step 4 [90].

- Step 1 – Data spikes: Occur as a result of temporary communication losses and metering equipment malfunctions. The spike amplitude can affect calculations accuracy despite their short time periods of occurrence [90]. Sudden and unexplainable data changes that fall outside operational limits indicate data spikes [89].
- Step 2 – Metering malfunctions: These may cause the logging of faulty data. They may be difficult to detect if the data and subsequent calculation results fall within the operational limits [90].

- Step 3 – Data loss: To identify data loss, indicators constituting data loss and the system not running need to be distinguished. Hence, an understanding of data loss indication by the specific system is necessary [90].
- Step 4 – Abnormal system operations: The removal of an abnormal measurement does not guarantee abnormal operation identification. Therefore, it is required that the dataset be further processed and analysed for the system operation to be evaluated objectively. Removal of measurement data during this step requires a good specific system operation understanding and consultation with all stakeholders involved [90].

The evaluation of findings will allow for an informed decision on whether the abnormality should be discarded or kept as part of the dataset.

2.4.2 Baseline model development

Various baseline models are available to assess and evaluate the impact of energy saving interventions. The choice of method depends on the number of identified energy drivers that have an impact on the energy consumption and the complexity of the system. This study uses linear regression modelling, with the production rate as the measurable independent variable and driving factor for energy usage.

According to Booysen [90], regression models with coefficient of determination (R^2) values greater than 0.75 indicate a good fit to the data points. Regression models satisfying this requirement can be used to determine the energy usage of the furnace as a function of the production tonnage. Energy savings post-intervention can be determined by the energy consumption difference for the same production between the baseline and performance assessment periods.

2.4.3 Evaluation of impact and benefit

The impact and benefit of the developed solution will be a reduction in natural gas consumption by the furnace. To evaluate the impact, the energy performance of the furnace when consuming only one of either natural gas or COG is essential. This is presented in Figure 22. It can be seen that more energy is used when consuming natural gas than COG for the same production tonnage.

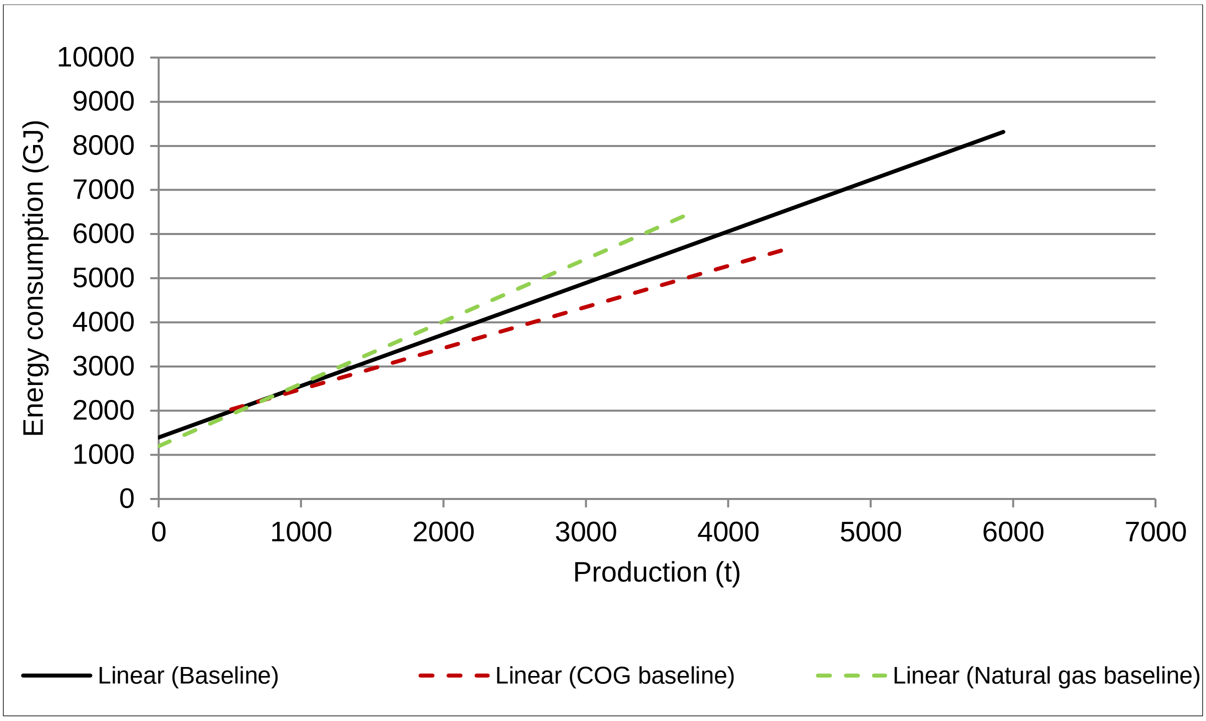

Figure 22: Furnace energy consumption baselines

Deviations by the actual usage from the baseline usage will be used to quantify the benefit by applying equation (20) [9].

$$E_{benefit} = E_{baseline} - E_{actual} \qquad (20)$$

Where:

$E_{benefit}$: Energy saving from benefit (MJ/Nm^3);

$E_{baseline}$: Energy consumption as per baseline period (MJ/Nm^3); and

E_{actual}: Actual energy consumption during benefit assessment period (MJ/Nm^3).

The potential cost savings were determined based on missed opportunities. The number of instances where the furnace temperature was unstable due to trial-and-error attempts by the furnace operators were identified from furnace log records. The records also indicate a switch to natural gas. These instances were identified as those during which the energy consumption did not correspond to the production output, i.e. higher energy consumption for a low production output. The average natural gas maximum price for the benefit assessment period in R/GJ was used for determining the monetary value.

There are certain conditions and restrictions that need to be considered when accounting for a saving taking place. The conditions for the benefit evaluation are:

- The reheating furnace must sustain the usage of only natural gas and COG as fuel sources and not introduce additional fuels.
- There must be sufficient COG supply available such that it is not mandatory for the furnace to utilise natural gas.
- Reductions in energy consumption as a result of plant stops or furnace idling due to maintenance, equipment failure and limited stock availability will not contribute as savings.

2.5 Conclusion

The utilisation of by-product gases as reliable sources of energy in steel milling facilities is accompanied by operational challenges. The challenges are due to the fluctuating nature of the CV of COG and the inconsistent availability of CV of COG measurement data to its high content of impurities. This results in inefficient management and control of the gas in combustion processes, to which the accurate air-fuel ratio is a critical factor. A generic solution was developed to improve the utilisation of COG in steel reheating furnaces.

The solution involves investigating and developing the gas network layout of the steel integrated manufacturing facility, including the identified gas producers and consumers. From the layout, the COG to steel reheating furnaces supply network was isolated. On the isolated layout, the PoMs for the COG data were required to be identified and indicated. The assessment and presentation of the data would provide information on whether the CV of COG was available.

For unavailable CV data, generic methods for estimating the unknown CV of COG were developed, presented and discussed. Three methods were developed and presented, namely, estimation using the coke-making process (Method 1), gas storage buffer (Method 2), and using coal and coke analysis (Method 3). A method to calculate the required air-fuel ratio of the furnace according to the gas CV and the current conditions or behaviours of the furnace was developed. A newly developed control philosophy is also presented and discussed. A baseline was also developed for quantification of the benefit of the developed solution.

3 RESULTS AND DISCUSSION: A CASE STUDY

Basic oxygen steelmaking [23]

[23] World Steel Association [BE], [Online] Available: steeluniversity.org. Accessed: 2019-10-10

3.1 Preamble

This chapter will validate the methodology developed in Chapter 2 through a case study. The methodology outlined a seven-step approach for the improvement of available coke oven gas (COG) usage in steel reheating furnaces while reducing natural gas consumption. The background information for the case study will be given, after which the stepwise methodology approach will be followed using the respective case study. The benefit of the solution will also be quantified.

3.2 Case study background

The solution methodology developed for this study in Chapter 2 will be verified through application on Plant A as a case study. Plant A is a billet mill that has a pusher-type steel reheating furnace, operating on a South African integrated iron and steel manufacturing facility. The plant reheats and produces billets, rounds, blooms and special profiles for trade in the local and international markets. The reheating furnace has a production capacity of 170 t/hr.

The furnace is designed to be fuelled by COG. However, natural gas is used as a supplementary fuel during COG supply shortages. This study considers furnace operations on COG combustion. The furnace comprises a total of five temperature control zones, namely preheating zone (PHZ), heating zone (HZ) and soaking zone (SZ). The HZ is subdivided into the top and bottom heating zones (THZ and BHZ), while the soaking zone is subdivided into east and west soaking zones (ESZ and WSZ). The furnace zones have individual gas consumption and combustion characteristics

The furnace is equipped with a recuperator that is used for the preheating of combustion air. The set-up is similar to that presented by Figure 19. The recuperator is accompanied by dilution, combustion and ejector fans. The dilution fan pre-cools the furnace off-gas prior to injection into the recuperator. The precooling is done to protect the recuperator from damage by the hot off-gas.

The combustion fan injects ambient air into the recuperator to be preheated to an elevated temperature. The ejector fan ejects the remainder of the excess air out of the furnace system through a furnace off-gas stack. The preheated air elevates the combustion flame temperature, thus contributing to energy efficiency improvement. The analysis of the contribution to energy efficiency improvement by preheated combustion air is not within the scope of this study.

The reheating furnace receives its steel products from the casting operations. The steel casts to be reheated can be stored on a bloom stockyard prior to being charged into the furnace or charged directly from the casting operations. This is a process referred to as direct or hot charging. This method of furnace charging improves the energy efficiency of the furnace. For the purpose of this study and in subsequent calculations, only steel charged from the bloom stockyard will be considered, i.e. reheating from ambient temperature, assumed as 25° C in subsequent calculations.

3.3 Implementation of methodology

3.3.1 Step 1: Steel facility gas network layout

The case study facility produces iron and steel using the blast furnace – basic oxygen furnace (BF – BOF) production route. Coke and sinter are produced on-site to be combined with other raw materials for the reduction of iron ore into liquid iron using the blast furnace (BF). The liquid iron is transported by torpedo ladles to the steel plant where it is refined into steel inside basic oxygen furnaces (BOFs). Continuous casters and rolling mills refine and shape the final product according to customer specifications.

The facility distributes COG, BFG and natural gas for production usage. The steel facility overall gas network layout for the case study is illustrated in Figure 23. The facility reclaims COG and BFG from the coke ovens and blast furnace, respectively, as process by-product fuel gases. The gases have separate supply networks with individual gas holders and flare stacks for surplus gas regulation. The facility uses the by-product gases in boilers for steam production. Steam is consumed by the plants and for on-site power generation by steam turbines and alternators

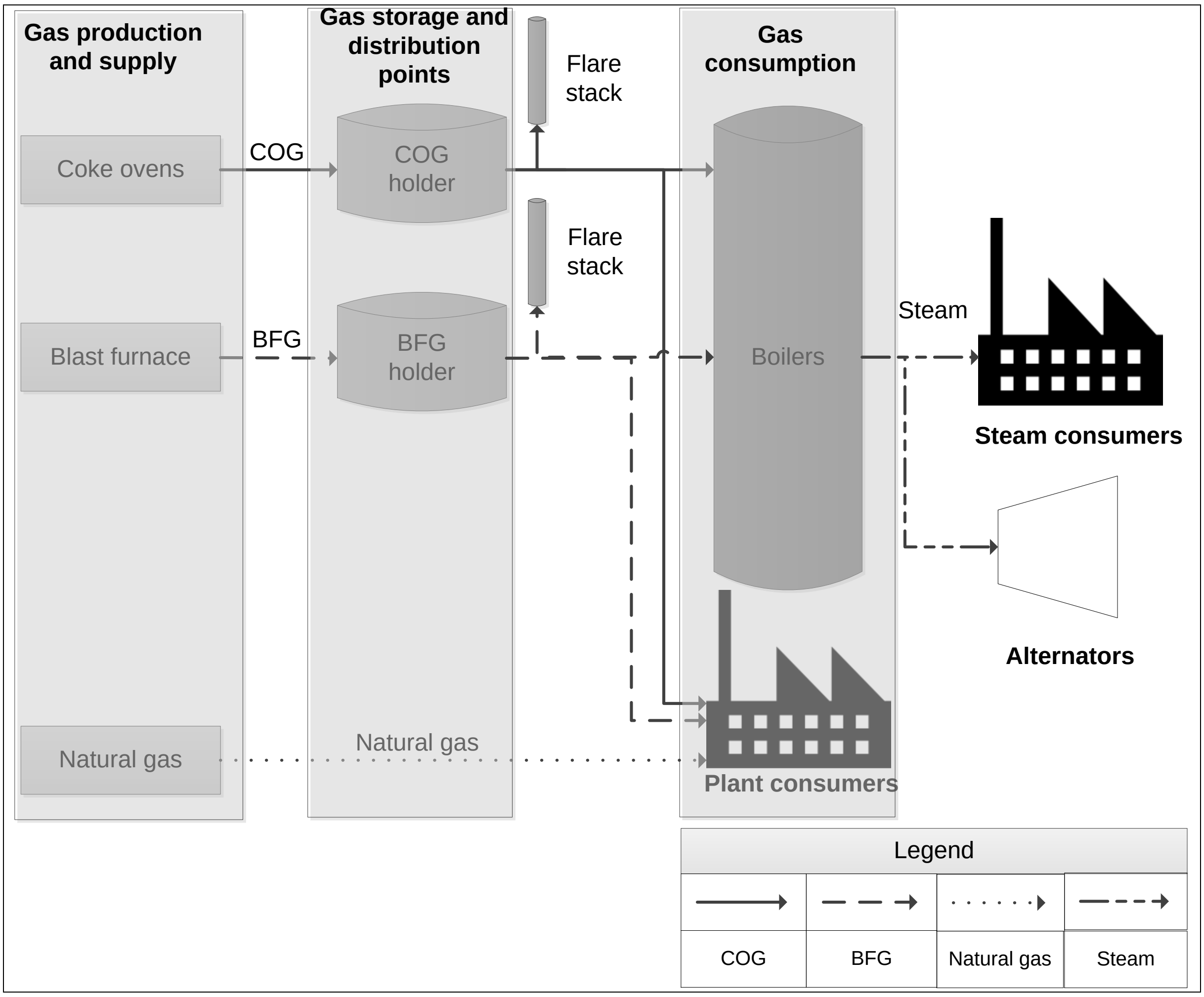

Figure 23: Case study steel facility gas network layout

The COG plant consumers include the steel mills, workshops, sinter plant, blast furnace and coke ovens. The COG holder has a capacity of 15 000 m^3, fed by a 1.8 m diameter pipeline. However, the facility operates on a strict 75 % maximum working capacity, and at a minimum of 15 %. The COG network pressure is regulated at 14 kPa.

When the gas holder reaches volumes above the maximum allowable capacity, the gas is flared. And when the minimum volume is reached, gas distribution is ceased until more gas is produced to recover the gas holder volume. The COG has a normal design flow velocity of 12 m/s. The BFG is consumed by the coke ovens, a gas plant and blast furnace stoves.

The BFG holder has a maximum capacity of 80 000 m^3, regulating the gas network pressure at a range of 10 – 12 kPa. The usable holder capacity range is within 64 000 – 80 000 m^3. Natural gas is purchased for usage by plants during by-product gas shortages. The facility sources natural gas from a local supplier, with a point of supply and distribution network within the facility.

3.3.2 Step 2: Coke oven gas to reheating furnaces supply network isolation

The COG produced within the works is distributed to and used by various consumers. From the coke ovens, the COG is cleaned at the by-product plant. The clean gas is stored in the COG holder until distributed for consumption by the consumers, including the steel mills. The distribution share is not automated, but rather determined and decided upon by a human operator.

The operator achieves this by considering gas availability and the demand for the gas as indicated by the various consumers. The facility has four steel mills, i.e. billet, medium, bar and rod mills. Each mill has a single reheating furnace, while the billet mill has two reheating furnaces. The COG to reheating furnaces isolated gas supply network is as presented by Figure 24.

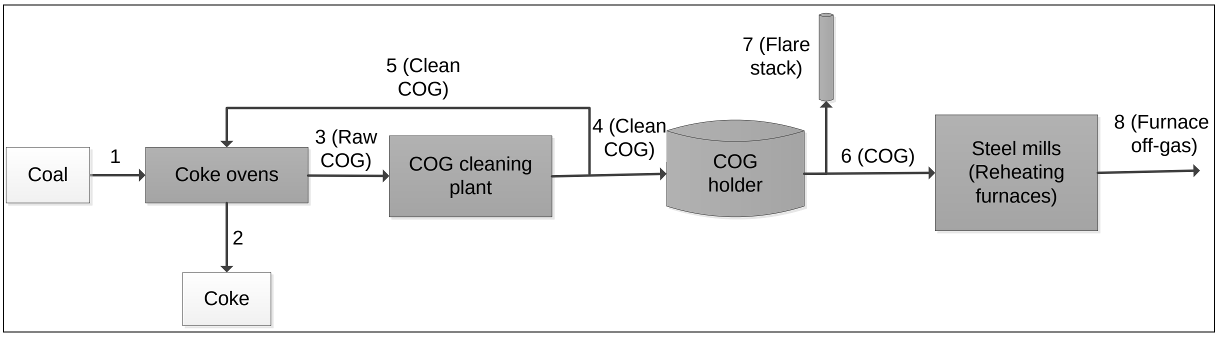

Figure 24: Coke oven gas to reheating furnaces supply network isolation

3.3.3 Step 3: Identification of required COG data and points of measurement

The reheating furnaces consume COG and natural gas for thermal energy needed for production. The CV indicates the maximum energy content of the gas, while the composition gives an indication of the required air-fuel ratio for the liberation of the energy from the fuel source. The CV of the natural gas and corresponding combustion air-fuel ratio is determined and provided to the facility by the supplier as indicated on purchase invoice documents.

The facility produces coke on-site for energy supply and iron-ore reduction in the blast furnace. The coke plant charges coal blends in various ratios as determined and optimised by the production personnel. The coal is 20 % imported and 80 % locally sourced. The facility has an on-site laboratory that analyses and reports on the quality and specifications of the various raw materials sourced and products produced. These analyses include the proximate and ultimate analysis of coal and coke.

The case study facility is equipped with a mass spectrometer and a Wobbe analyser used for analysing COG. These instruments are calibrated according to original equipment manufacturer (OEM) specifications to validate their accuracy. Calibration certificates were made available. The mass spectrometer is installed before the COG holder, while the Wobbe analyser is located after. According to Figure 13, the mass spectrometer presents the PoM on stream (4) and the Wobbe analyser stream (6). The mass spectrometer provides data readings on gas density, composition, average molecular weight, Wobbe index, combustion air-fuel ratio and CV. Sample readings are manually taken by plant personnel.

The Wobbe analyser provides data on the gas density, Wobbe index, combustion air-fuel ratio and CV. The analyser continually reads the data as the gas flows to the consumers. The PoM closest to the reheating furnace is the most critical as the furnace energy usage and combustion process are controlled effectively when using the data it gives, provided that the data is evaluated and its accuracy ensured. Composition analysis for stream (6) may be acquired from the supervisory control and data acquisition (SCADA) upon request.

The points of COG data measurement for the facility are as presented by Figure 25. Plant personnel have also indicated that the mills were previously retrofitted with furnace off-gas analysers. However, the gas analysers were eventually removed as they required an intense maintenance routine due to constant clogging when combusting COG.

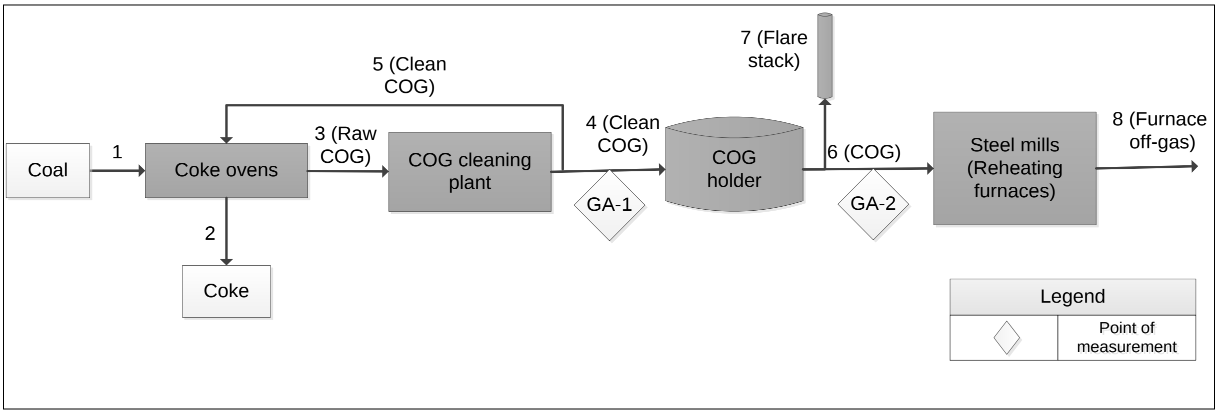

Figure 25: Points of measurement for CV of COG for case study

In subsequent sections, the mass spectrometer and Wobbe analyser of the case study will be referred to as gas analyser 1 (GA-1) and 2 (GA-2), respectively. Figure 26 is representative of the overall layout and data presentation of the COG to steel reheating furnaces for the case study.

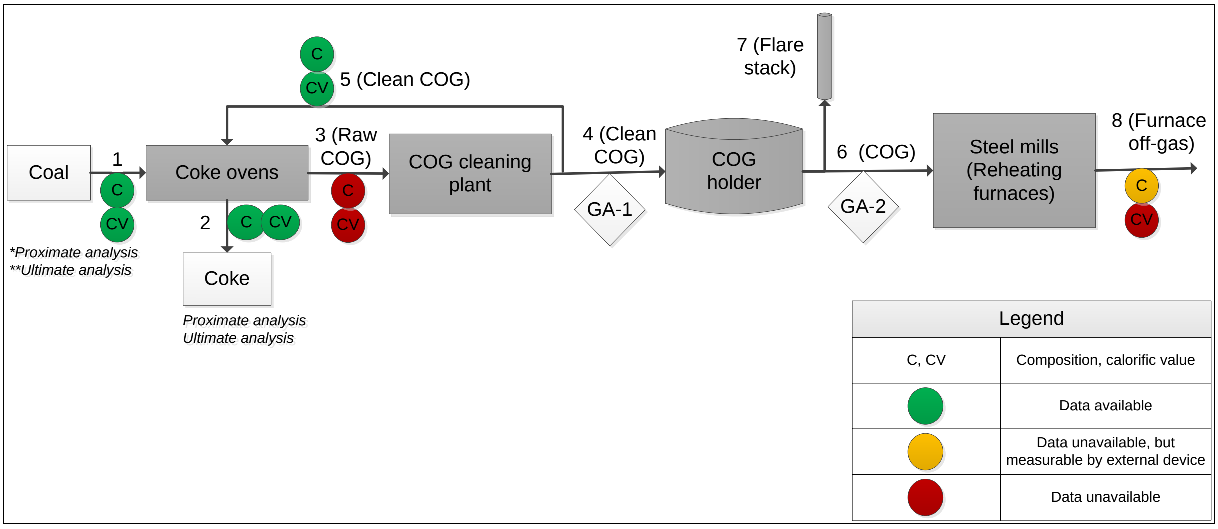

Figure 26: Case study isolated COG to reheating furnaces network showing PoMs

3.3.4 Step 4: Data assessment and information presentation

This step in the methodology indicates that the available data needs to be assessed and evaluated. This is achieved by evaluating the question, "*Is CV of COG or composition data available?"* from Figure 10. The data obtained from GA-1 and GA-2 is used for this evaluation. As described in the methodology, the question may be evaluated with either a "Yes" or "No" outcome.

Available CV of COG data

It has been indicated that for combustion process monitoring and control, the CV of the fuel and the corresponding air-fuel ratio are critical. The facility has installed a RHADOX 3000 Wobbe Index Analyser, referred to as GA-2 in the context of this document. To verify the measured data, calibrations of the meter were done according to the original equipment manufacturers (OEM) specifications. Calibration certificates were availed and assessed

The data available and presented in Figure 27 illustrates an evaluation of question (A) of Figure 10 with a "Yes" outcome. GA-2 measures the CV of the COG and provides its corresponding air-fuel ratio. This analyser is closest to the reheating furnaces and the data can thus be used directly to manage and control the furnace combustion of COG and the temperature. The data is available to the operators through the electronic graphic displays available in the furnace control rooms.

The visual presentation of the CV of COG 24-hour profile example, shown in Figure 27, clearly shows its fluctuating nature. The CV of COG ranged between maximum and minimum values of 21,6 MJ/Nm^3 and 13,2 MJ/Nm^3. Various degrees of gas CV fluctuations were noted. The corresponding air-fuel ratio, as provided by GA-2, and the actual air-fuel ratios for the respective zones, are also presented.

It can be seen that the actual air-fuel ratios are significantly different from that provided by GA-2. The actual air-fuel ratios are also different for the different zones. The actual air-fuel ratios were established by the furnace operators using a trial-and-error method. The occurrence of such fluctuations requires reliable methods for air-fuel ratio adjustments to control the furnace temperature, and to maintain stability.

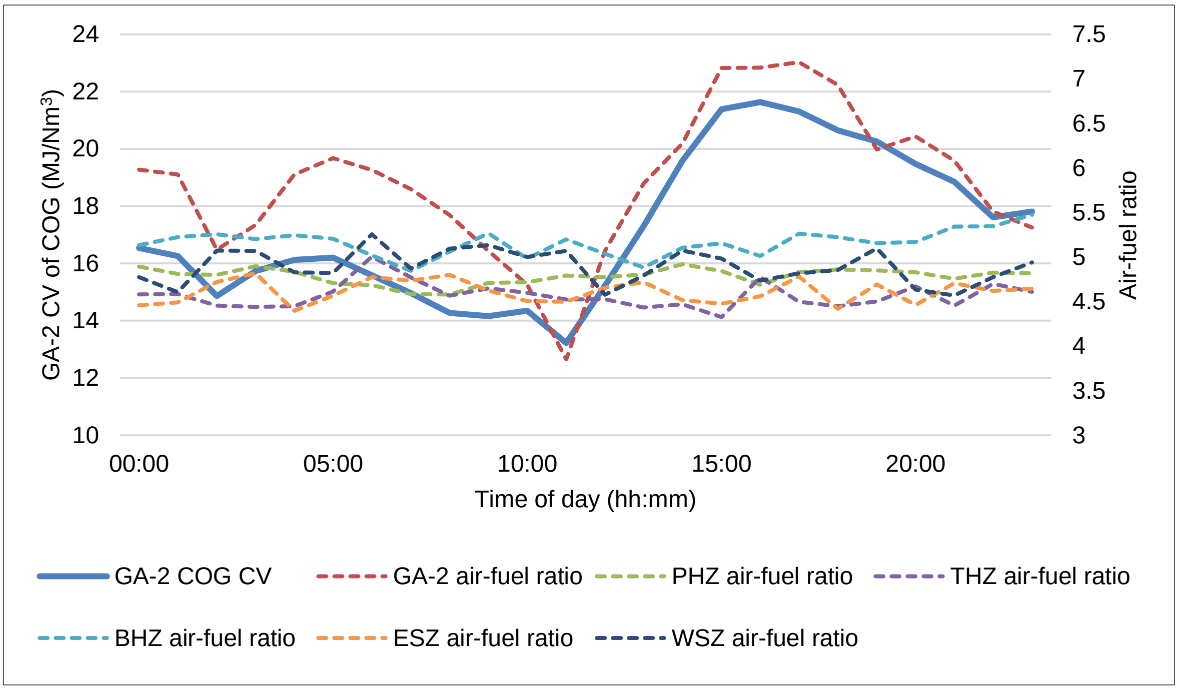

Figure 27: GA-2 CV of COG and air-fuel ratio

Unavailable CV of COG data

Prior discussions have elaborated on the uncertainty of data brought upon by the use of measuring equipment. Metering malfunctions and data loss have been identified as one of the sources of erroneous data. For the present case study, the data collected from GA-2 is regularly faulty as a result of the identified error sources. This leads to evaluating question (A) of Figure 10 with a “No” outcome.

From the available facility data set on CV of COG from GA-2, the duration of the events during which CV data is unavailable due to meter malfunctions was investigated. It was found that CV of COG data would be unavailable for a duration between 2 – 24 hours. An extreme case of a duration of 20 days during which CV of COG data was unavailable due to the clogged analyser was identified. This extreme case was due to the absence of the responsible maintenance personnel from the facility during that time.

Figure 28 presents examples of faulty data collected from GA-2. Shown by the graph is faulty data caused by the clogging of the analyser. The clogging is due to the impurities that remain contained in the gas. When clogged, the analyser presents a default reading of 25 MJ/Nm^3 for CV of COG and 4,8 for the air-fuel ratio. The lack of knowledge on the energy content of COG aggravates its inefficient usage.

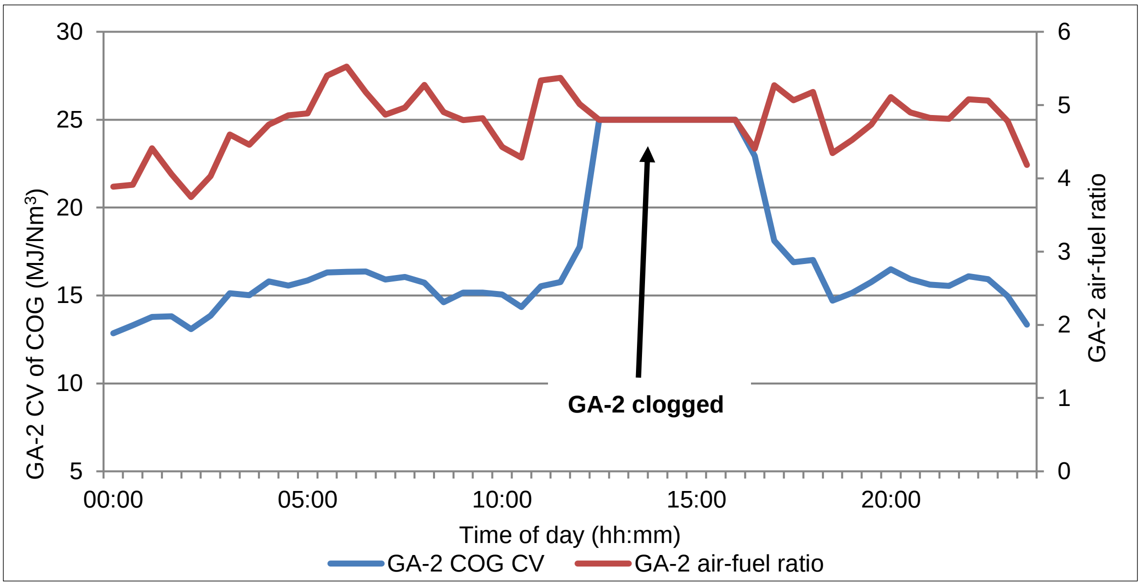

Figure 28: GA-2 unavailable CV of COG data

Estimation of unknown calorific value of coke oven gas

The previous section showed the need for the development of alternative reliable methods to estimate the unknown CV of COG. Three methods were developed and discussed for this purpose. The case study will be used for validation of the methods.

Method 1: Estimation of unknown CV of COG – The coke-making process

This method uses actual available CV of COG measurement data from GA-1 for the investigation of the gas CV profile with process time. GA-1 is a mass spectrometer that takes measurements of the CV of COG at the PoM on stream (4) as per COG network layout, shown in Figure 29. The readings are manually administered by a plant operator. The readings are taken at 3 – 5-hour intervals.

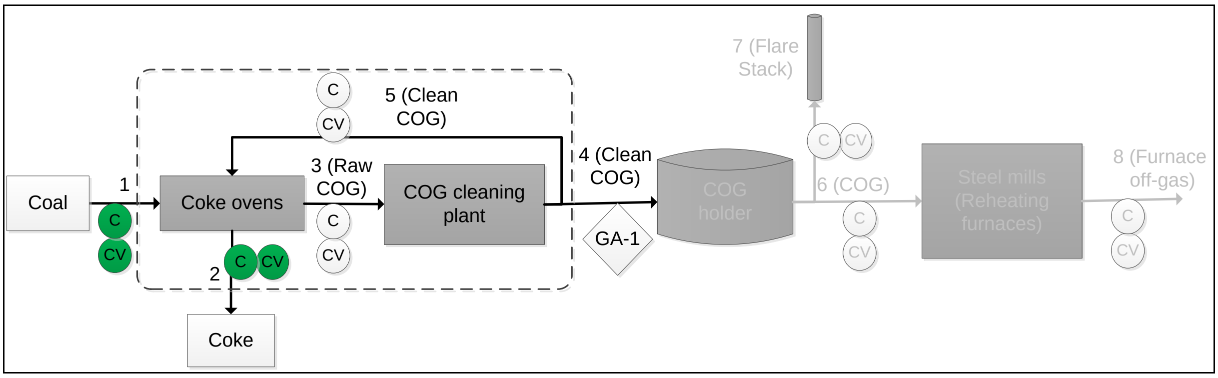

Figure 29: GA-1 for CV of COG estimation by Method 1

Figure 30 represents the CV of COG profiles from GA-1 for eight consecutive coke production days. It can be observed that for seven of the eight days, the CV of COG profiles display similar trends. It can be deduced that this particular plant starts its production cycles at 07h00 daily as it is the time where the highest CV of COG reading of the cycle begins. The readings show a gradual declining trend of the CV of COG through the progress of the cycle. The beginning of a new cycle can be detected until the highest reading again on the next day.

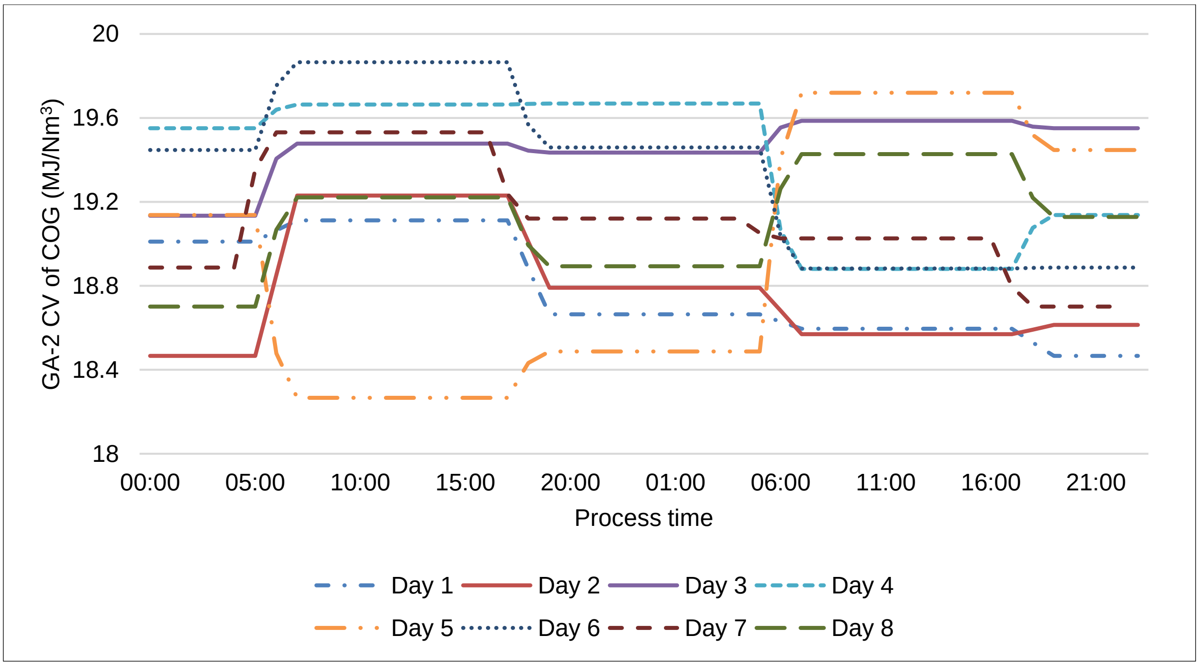

Figure 30: CV of COG profiles with respect to process time

Day 5 displays a different profile, which implies that production was started at a later time on that day. On Day 4, the second reading was not taken. Profiles for a total of 30 days were analysed. The concept discussed is revealed, however, there are some deviations as observed. Presented in Figure 31 in the CC for validating Method 1.

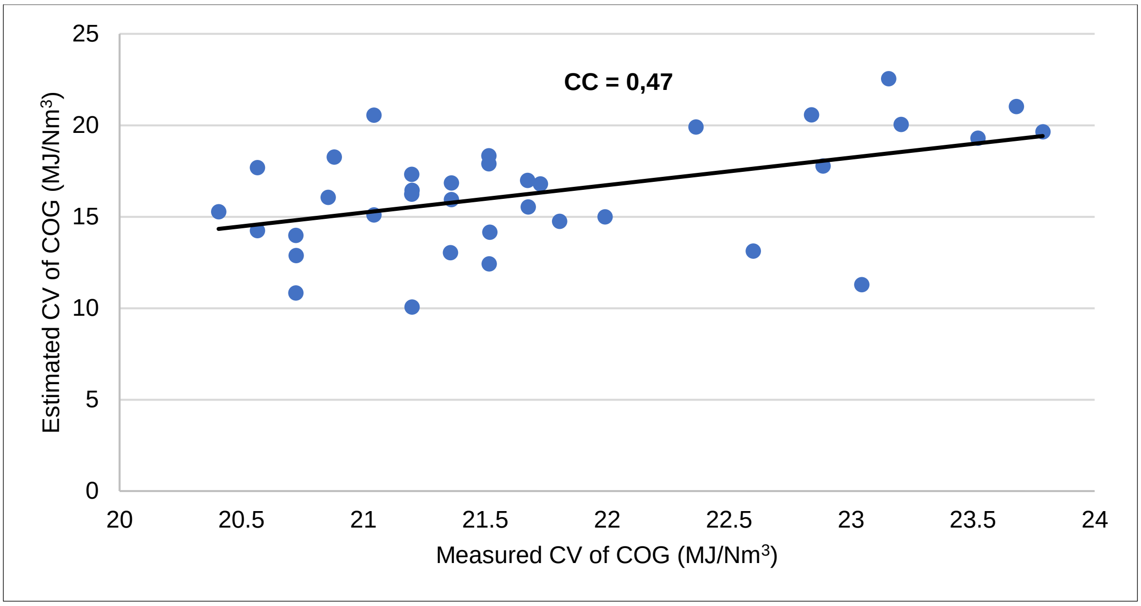

Figure 31: Correlation coefficient of Method 1

For the validation of Method 1, the correlation coefficient (CC) was determined as 0.47, while the mean average error was 4.3 %. These results are presented in Table 9. The CC value is not as close to 1 as desirable. The concept behind the development of this method for CV of COG estimation is sound and practical. However, the lack of frequent readings makes it difficult to conclude its validation. This is because it has already been established that the CV of COG fluctuates frequently, therefore, frequent readings are required prior to a solid validation of the method.

Table 9: Validation of Method 1

Validation parameter	Value
Correlation coefficient (CC)	0.471
Mean absolute error (MAE)	4.3 %

Method 2: Estimation of unknown CV of COG - Gas storage buffers

This method uses the available CV of COG data from GA-1 to estimate the unknown values at GA-2, considering the boundary as shown in Figure 32. Equation 2 was applied for the relevant calculations. This equation indicates that the buffer outlet CV of COG is dependent on the volume of the gas in the buffer, the gas flowrate and the incoming COG. The estimated values were compared to a dataset of the actual, measured values from GA-2.

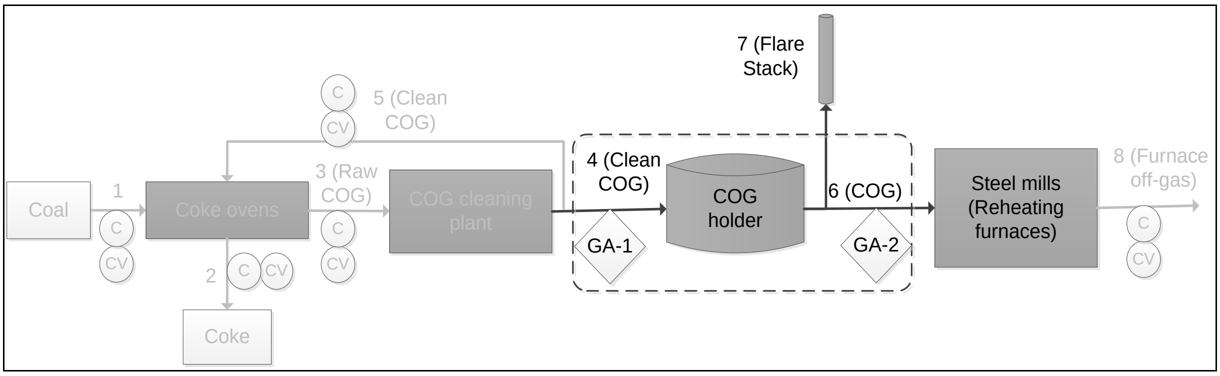

Figure 32: Representation of GA-1 and GA-2 for Method 2

Preliminary calculations showed that the buffer incoming CV of COG (GA-1 CV of COG) has a direct impact on the outgoing CV (GA-2 CV of COG). The other variables' effects were shown to be negligible. Hence, subsequent calculations based on Method 2 assume a constant buffer volume and gas flowrate. The buffer residence time was determined as 6 minutes and 8 seconds, i.e. the time delay due to the buffer. Application of Green's test method indicated that a minimum of 58 samples is representative of the data pool and can thus be used for verifying the method.

Presented in Figure 33 is a comparison of the estimated and measured CV of COG values for the buffer method. It can be seen that the data points for the two data sets are relatively close. Minor deviations from each other can be observed for moments when the values start to increase following a prior trend of a decrease, and vice versa. This may be attributable to cumulative errors from calculations of the estimated values.

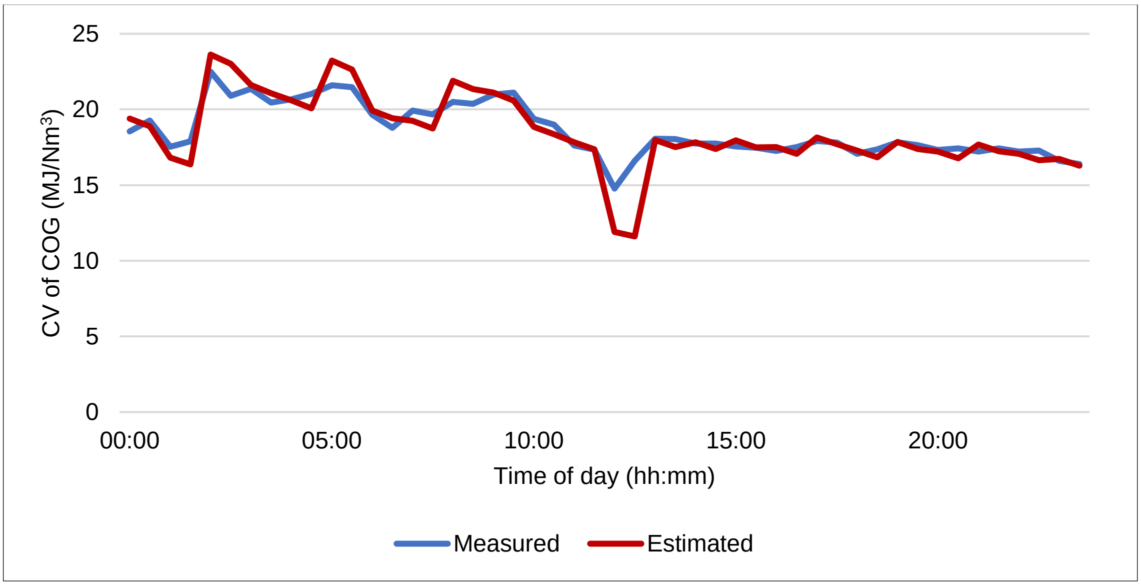

Figure 33: Method 2 comparison of measured and estimated CV of COG

Figure 34 presents the validation of Method 2 using the CC criterion. It has been stated that a CC value of 1 is desirable as it reflects complete accuracy for the model. For the present study, a CC value of 0,961 was obtained. Deviation from the value of 1 may be attributable to the possibility of plug flow interaction of the gas in the buffer i.e. imperfect mixing or homogenisation. It was also indicated that GA-1 readings are administered manually, hence human error is attributable to the deviation from accuracy. This could also be the cause of the wide variety in the data points between 20 MJ/Nm^3 and 23 MJ/Nm^3.

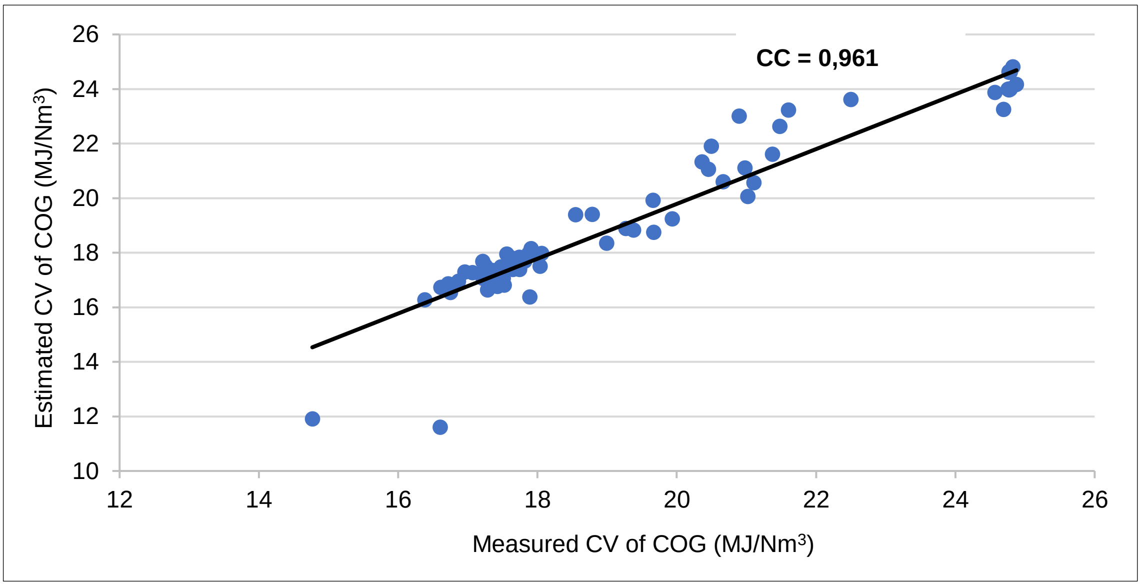

Figure 34: Correlation coefficient of Method 2

The second criterion applied to validate the estimation method is the MAE. The MAE value has been determined as 0,568 %, as seen in Table 10. A small MAE is indicative of method accuracy. The used criteria therefore indicate that Method 2 is accurate, reliable and can be used for CV of COG estimations over a gas buffer. The measured and estimated CV of COG values were normalised at 25 °C and 1 atm.

Table 10: Validation of Method 2

Validation parameter	Value
Correlation coefficient (CC)	0,961
Mean absolute error (MAE)	0,568%

Method 3: Estimation of unknown CV of COG - Products of combustion

The use of Method 3 requires the compositional data of the furnace incoming COG and the off-gas. COG samples were requested for analysis, and the off-gas analysis data was acquired as per the methodology described in section 2.2.5. Available CV of COG data from GA-2, as shown in Figure 35, will be used as the measured dataset for comparison with the estimated values. The analysis of the furnace off-gas identified the presence of the following species as the products of combustion:

- Carbon monoxide (CO)
- Carbon dioxide (CO_2)
- Sulphur dioxide (SO_2)
- Nitric oxide (NO)
- Nitrogen dioxide (NO_2)

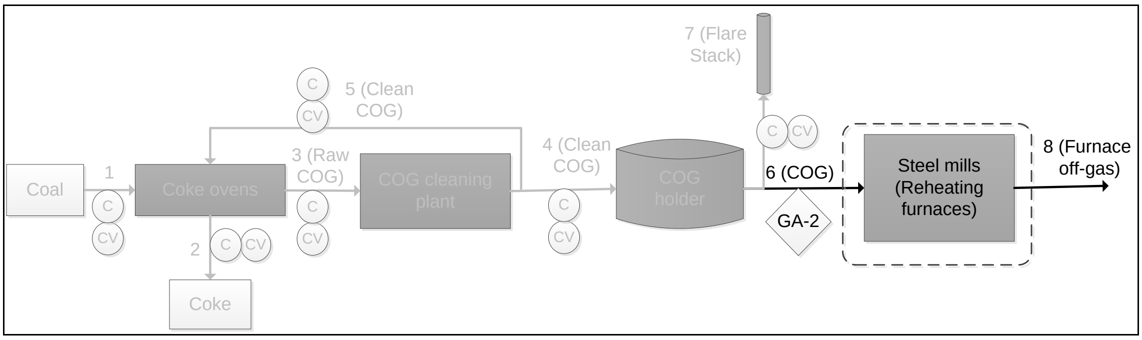

Figure 35: Representation for GA-2 for Method 3

The comparison between the measured and estimated CV of COG values using Method 3 is presented in Figure 36. Compared to Method 2, a significant difference between the two data sets can be observed. The measured values are significantly higher than the estimated values. Observing the species constituting the products of combustion from the analysis, water vapour is not included. Therefore, the latent heat of condensation was not accounted for in the calculations associated with Method 3.

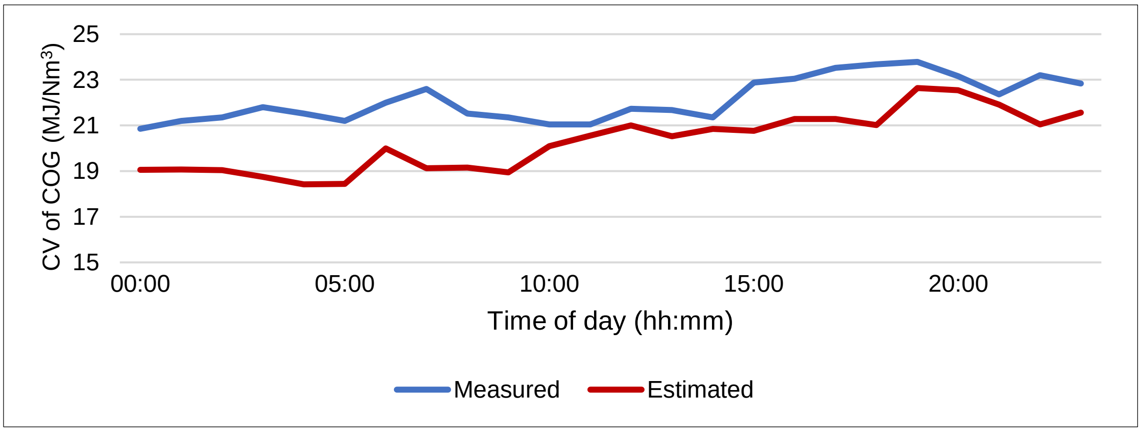

Figure 36: Method 3 comparison of measured and estimated CV of COG

This shows that by using Method 3, it is the lower calorific value (LCV) of the fuel that is being estimated. Accounting for the latent heat of condensation of water vapour gives the higher calorific value (HCV) of the fuel gas. It can, therefore, be said that the GA-2 analyser provides measurements for the higher CV COG. This is seen in the precision of the data as reflected by a closely similar profile of the two data sets. Improvement of Method 3 will require condensing the products of combustion for the detection of water vapour.

Method 3 was also validated using the CC and MAE statistical parameters. Figure 37 shows the CC value determined, which is 0,794. This value significantly deviates from the ideal value of 1. It can be said that using Method 3 introduces some degree of inaccuracy and error in the estimated values. As already discussed, the latent heat of condensation of water vapour, which is a constituent of the products of combustion, was not accounted for in the estimation of the values. Accounting for latent heat of condensation of water vapour would increase the estimated values, thus increasing the CC towards the desired value of 1.

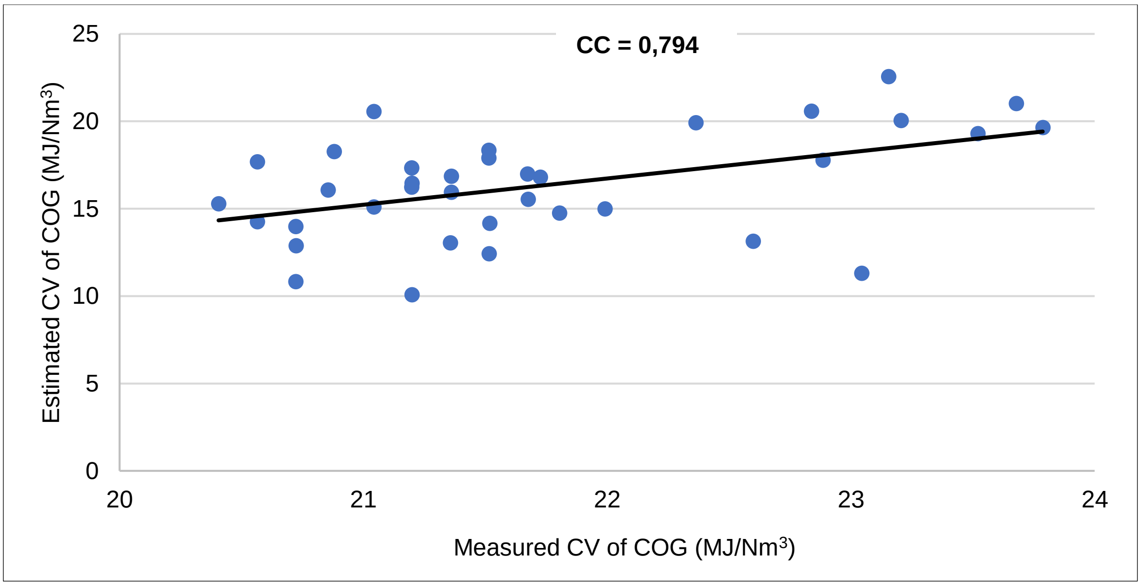

Figure 37: Correlation coefficient of Method 3

The determination of the MAE returned a value of 1,996 %. This value is also higher for Method 3 than it is for Method 2. This indicates that when one has the option to use either one of the methods, Method 2 should be prioritised. If Method 3 must be used, the possibility of the furnace off-gas analyser measuring water vapour after condensation of the products of combustion must be explored. The CC and MAE for Method 3 are represented in Table 11.

Table 11: Validation of Method 3

Validation parameter	Value
Correlation coefficient (CC)	0,794
Mean absolute error (MAE)	1,996 %

3.3.5 Step 5: The developed air-fuel ratio methodology

This study developed a method for determining the adjustments of the combustion air-fuel ratio according to the calorific value of the fuel and the current operating conditions of the furnace. The air-fuel ratio model was developed as described by the methodology in Section 2.2.6. The verification of the methodology will be done through simulation models and validated through practical tests on a billet mill furnace. The verification and validation studies seek to find the effects of the changing calorific value and corresponding air-fuel ratio on the temperature output of the furnace. The verification methodology is discussed in the following section.

3.3.6 Step 6: Verification of air-fuel ratio determination methodology

Prior to implementing a different operating strategy on a plant, it is good practise to predetermine the response of the system to the new inputs. This is the first step to analysing the feasibility of the solution and its compatibility with the system. This can be achieved by the development and use of system simulation models. The accuracy of the simulation models is significant because its purpose is to mimic the actual plant and system behaviour.

Microsoft Excel was used for the modelling and simulations of the furnace operations. The furnace system models were developed from theoretic principles of design and operations. Then actual furnace data from various operating periods were fit into these models for simulations and the calibration of the simulation models.

For the present study, the effects of the changes in CV of COG and the corresponding air-fuel ratio on the temperature of the furnace are of interest. Therefore, the furnace temperature is the key performance indicator for the present simulation studies. The simulation model was built following theoretic principles and using actual furnace data for calculations.

The furnace can consume a combination of the gases in any desired configuration, but the zones can only consume one of the fuel gases at a time. The temperature control zones are fitted with different numbers of burners that have different capacities. The number of fitted burners per zone and their capacities are shown in Table 12. The individual zones are also fitted with thermocouples for local temperature measurements.

Table 12: Furnace zone specifications and constraints

Temperature control zone	Number of burners	Maximum burner capacity (GJ/hr)	Zone temperature set point (°C)	Fuel gas consumed
PHZ	4	10.7	1 250	Natural gas or coke oven gas
THZ	12	10.1	1 290	
BHZ	10	10.7	1 300	
ESZ	15	1.15	1 300	
WSZ	15	1.15	1 300	

3.3.7 Step 7: Validation of simulation results: Practical application to a case study

The simulation results were validated through a practical application on a billet mill reheating furnace on Plant A. For the validation pilot studies, properties of the actual independent variables (CV of COG, furnace load and steel profiles, charge temperature, COG composition) were used as inputs into the models. The outputs of the models (furnace zone temperature and air-fuel ratio) were observed against the actual furnace outputs. The pilot tests were performed over a duration of 6-hours at a time. The overall results for the respective furnace zones will be presented and discussed in this section. The operating specifications are given in Table 13.

Table 13: Operating conditions for practical tests

Operating conditions	
Furnace	Billet mill F1
Rolled profile	131 x 131
Charge temperature	25° C
Fuel gas	COG

The profiles for the CV of COG and the corresponding air-fuel ratio (GA-2 air-fuel ratio) during the practical tests are shown in Figure 38. In Figure 38, GA-2 air-fuel ratio represent the actual measured air-fuel ratio, while the others show the simulated air-fuel ratio values. To perform the tests, the actual CV of COG at the given time was inserted into the developed model, which gave the air-fuel ratio value. The calculated air-fuel ratios for the respective zones are also presented in Figure 38.

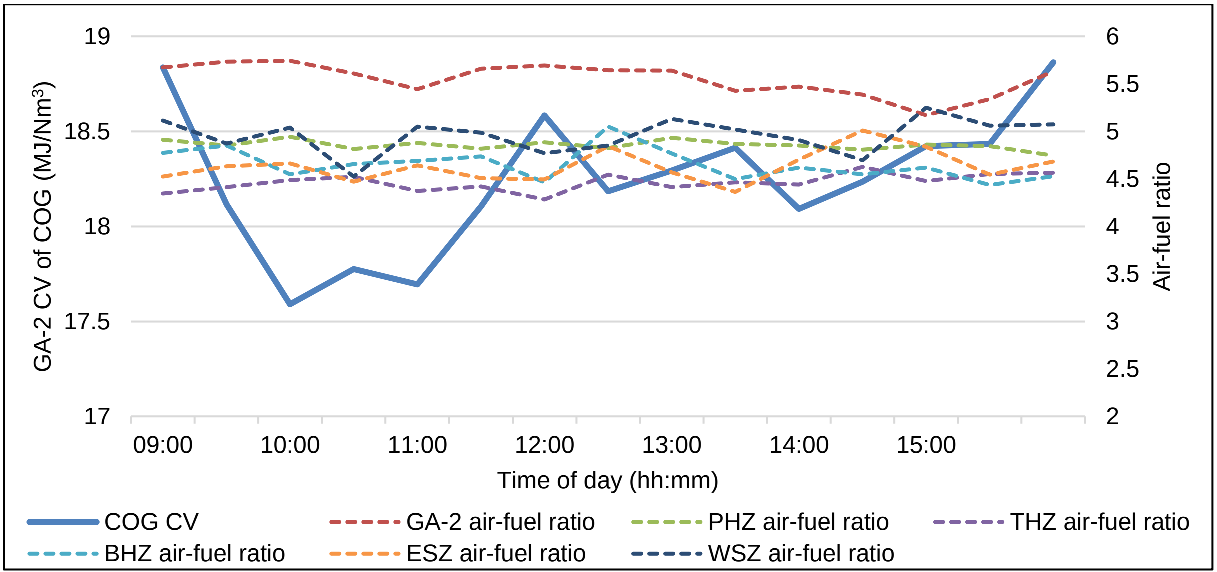

Figure 38: CV of COG profile

It can be seen from Figure 38 that the model calculated air-fuel ratios that are significantly different from the one provided by the analyser (GA-2 air-fuel ratio). The air-fuel ratios for the respective zones remain different from each other as well. For the respective zones, the determined air-fuel ratio values were manually inserted into the control receiver, and the responsive temperatures were observed. The presented results compare the simulated and actual temperatures.

The practical temperature test results for the preheating zone (PHZ) are presented in Figure 39. It can be seen that the simulated and actual temperatures present relatively similar and consistent profiles. However, the actual temperature is consistently lower than the simulated temperature. The lower actual temperature can be attributed to the heat losses from the opening and closing of the furnace doors during the charging of steel. An average error of 6 % between the simulated and actual temperature was identified.

This is because the steel is introduced to the furnace from the stockyard by being charged through the PHZ. The energy loss that occurs during the opening and closure of the furnace doors can be quantified through energy balance studies. The quantification of the energy loss and prevention, thereafter, could result in additional fuel and cost savings for the furnace.

Another significant deviation between the two temperature profiles can be seen at time 13:15. This was due to the zone being put on idle because of unavailable steel from the stockyard.

During idling, the simulated temperature remained at a higher value than the actual. This indicates that the temperature effects of the furnace door openings during steel charging and the idling events were not accurately accounted for in the simulation modelling and calibration exercises.

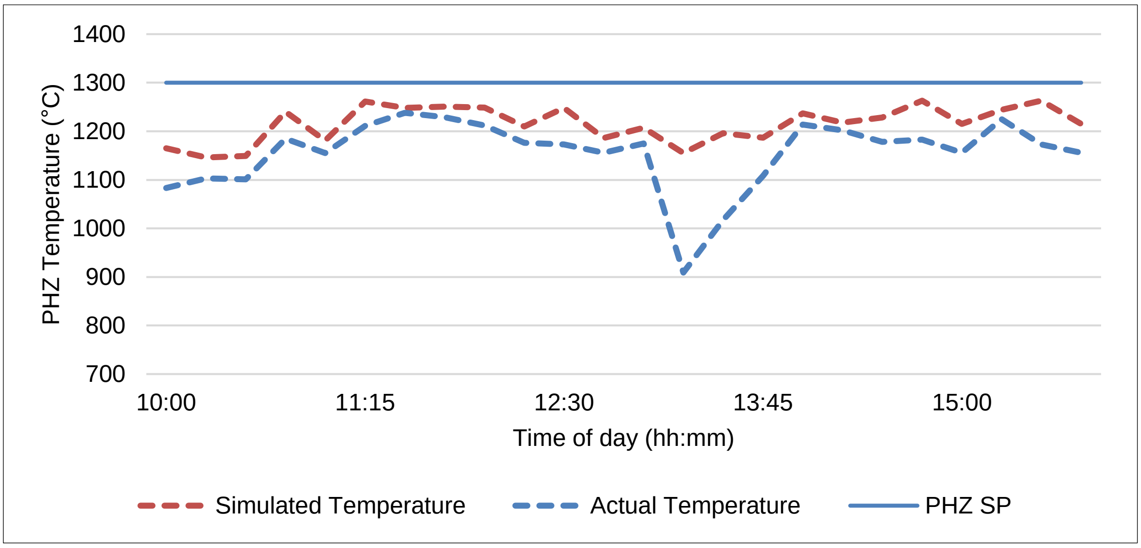

Figure 39: Furnace temperature tests: PHZ

Similar tests were performed for the top heating zone (THZ). The temperature profiles are presented in Figure 40. The two profiles also followed a relatively similar trend. Stability of the temperatures is seen, regardless of the fluctuating CV of COG.

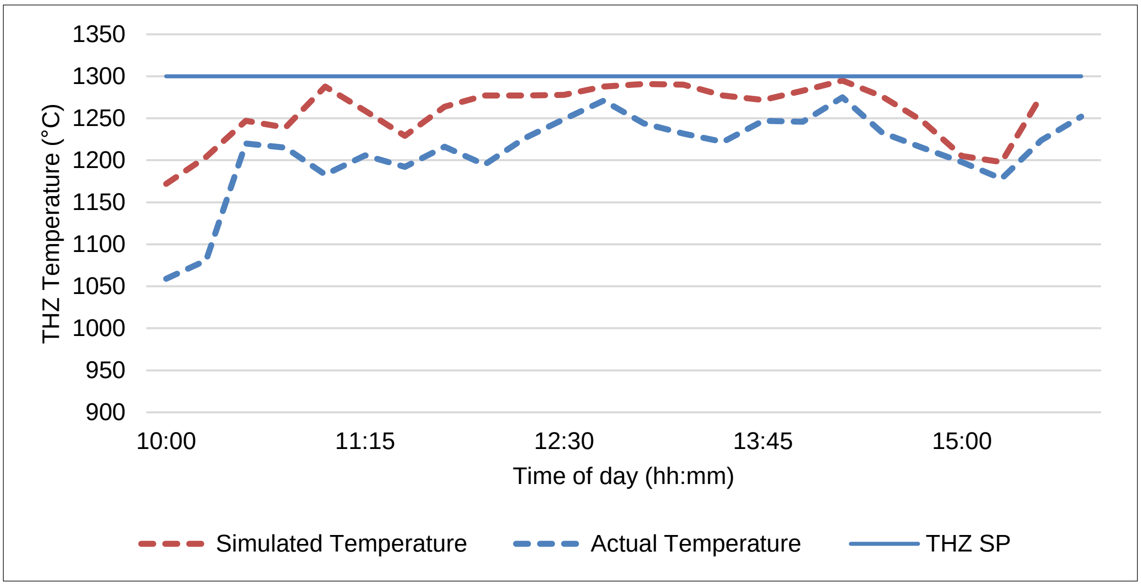

Figure 40: Furnace temperature tests: THZ

This shows the significant impact of the appropriate air-fuel ratio. The simulated temperature is also consistently higher than the actual temperature. This may be due to malfunctioning, aging or clogging of the burners. Thus, they are unable to deliver the maximum possible temperature output. An average error of 4 % between the simulated and actual temperatures for the THZ was determined.

The results of the practical tests on the bottom heating zone (BHZ) are presented in Figure 41. The simulated and actual temperature profiles show closely similar profiles. Like the THZ, the simulated temperatures are higher than the actual. Also, the simulated temperature is seen to maintain stability and remained closer to the temperature set point (SP) than the actual temperature. It can be said that, given the bigger size of the BHZ, and the THZ alike, significant energy losses are probable. Hence the furnace tests show lower actual temperature values. The simulation and actual temperatures for the BHZ show an averaged 4 % error.

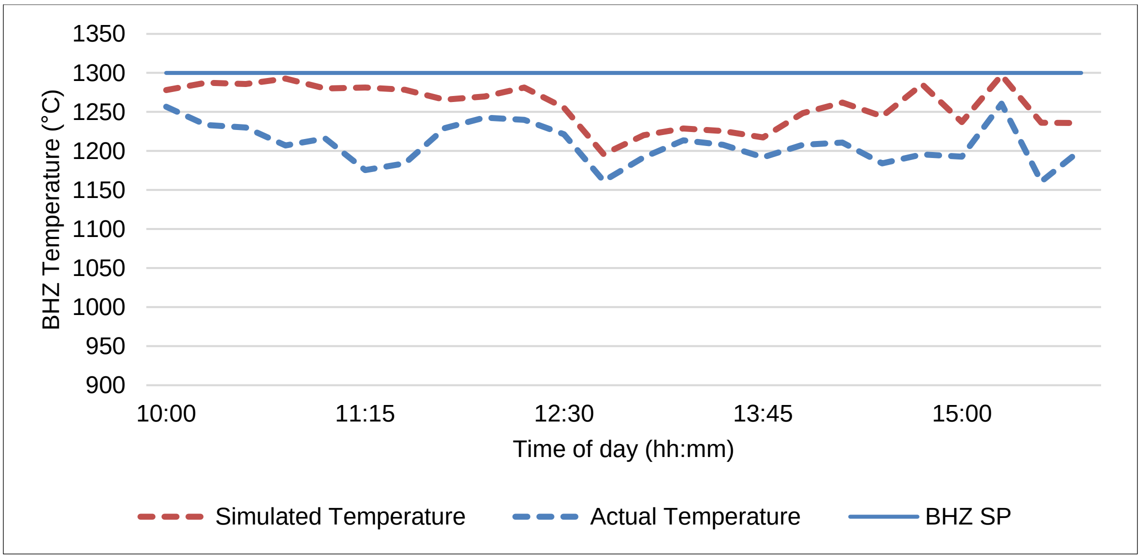

Figure 41: Furnace temperature tests: BHZ

The tests results for the east and west soak zones (ESZ and WSZ) are shown in Figure 42 and Figure 43, respectively. For the smaller zones, the practical applications showed that the actual temperature remained higher than the simulated. This is attributed to the effects of thermal coupling among the furnace zones. This indicates that the effects of thermal coupling were not accurately accounted for in the modelling and simulations. Thermal coupling effects were observed to be more significant in the smaller zones (ESZ and WSZ) than the larger zones. The ESZ and WSZ have equal errors of 2 % between the simulated and actual temperatures.

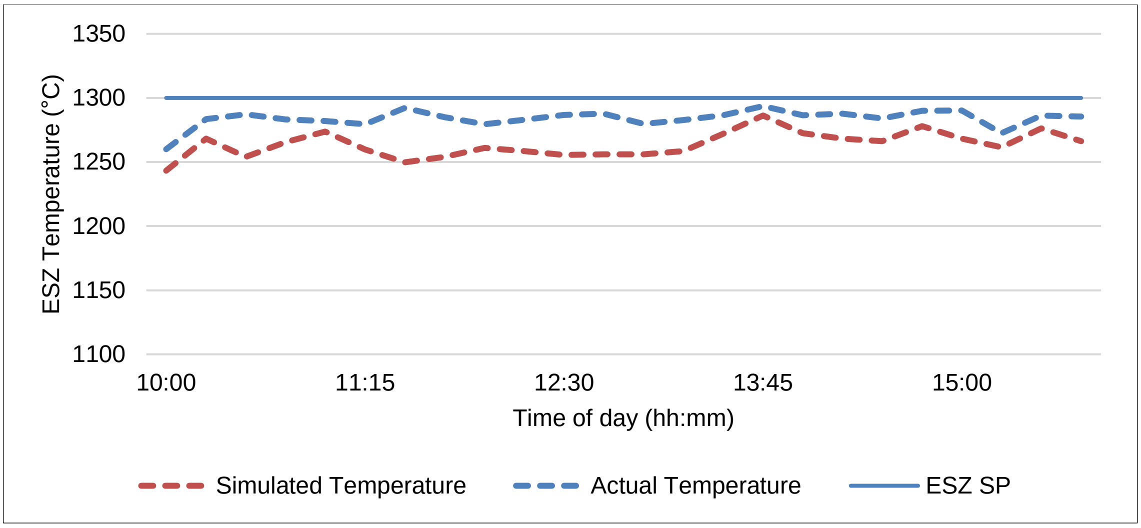

Figure 42: Furnace temperature tests: ESZ

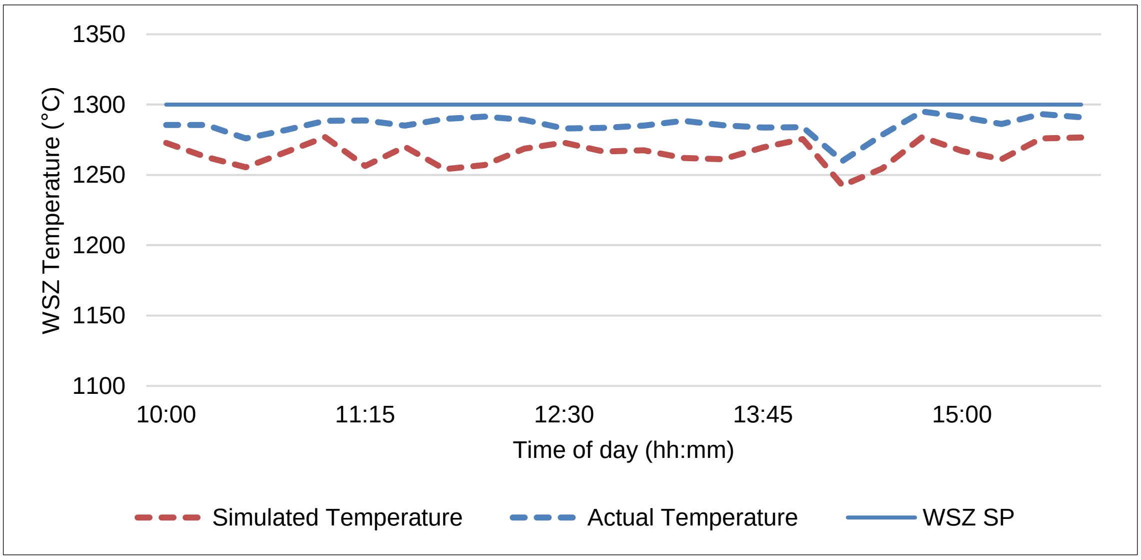

Figure 43: Furnace temperature tests: WSZ

Discussion and summary of results

The aim of the practical application studies was to validate the results of the effects that changes in CV of COG and the corresponding air-fuel ratio have on the temperature of the furnace. The measurements used for this study may be said to be accurate since there are multiple thermocouples used within the furnace, and the readings from the thermocouples are within a 5% proximity to each other.

For the PHZ, BHZ and THZ, actual temperatures observed were lower than the simulated. This can be attributable to energy losses due to these zones being of a large size. The furnace zone energy profiles can be modelled to quantify the energy losses. The clogging of the burners and pipelines due to COG impurities may also reduce the required gas volume that has to be combusted, as per the model and simulations calculations. Therefore, the actual temperature output is lower than expected.

Also, the accuracy of the actual measured temperature by the thermocouples is arguable due to errors associated with the use of measuring equipment. The furnace zones are equipped with multiple thermocouples. This is because the temperature across the entirety of the furnace is not uniform. Hence, the furnace data report the lowest temperature measurement from the thermocouples in order to be able to detect any process malfunctions.

The study simulations and practical application focused on the effects of CV and air-fuel ratio on the temperature performance of the furnace. However, there are other existing factor changes that affect the resultant temperature output, which were not accounted for in the modelling and simulations. These were identified as furnace idling, profile changes and furnace door openings and closings during the charging of the steel.

The average error between the simulated and actual temperatures was shown to range between 2 %– 6 %. This indicates that the developed methodology achieved the desired objective. However, the individual results for the zones indicate the need for finer tuning to improve temperature stability. This will require further studies to accurately quantify the extent of the impact of furnace energy losses and thermal coupling.

3.4 Quantification of benefit

For the quantification of the benefit of the solution, a single variable regression baseline model was developed. The resulting model is presented in Figure 44. The model regressed the furnace daily production and energy usage data over a 10-month period prior to the pilot study tests, i.e. January to October 2017. The baseline data quality was evaluated as per the method described in Section 2.4.1.

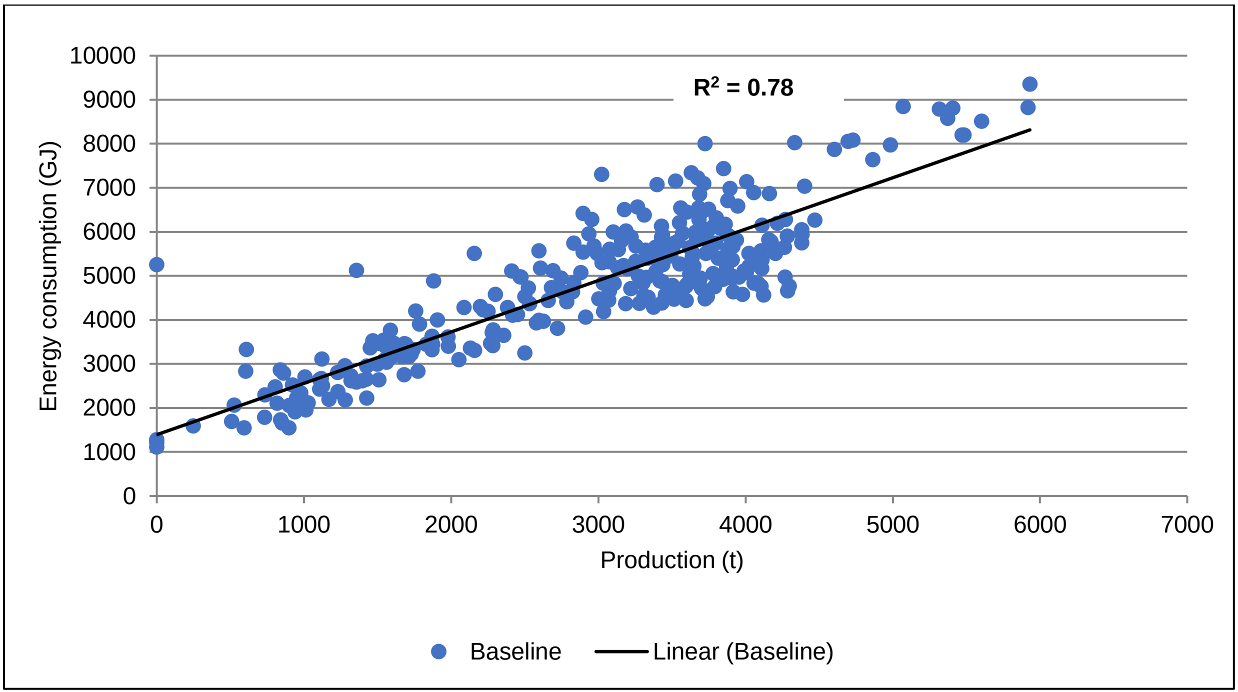

Figure 44: Furnace energy regression model

The regression model returned an R^2 value of 0,78. This baseline model satisfies the requirements of a minimum R^2 value of 0,75 as indicated by Booysen [90]. This also shows a direct correlation between the production tonnage and the furnace energy consumption. Therefore, Figure 44 is considered as being representative of the normal operations of the furnace. Therefore, the developed model will be used for the quantification of the energy savings benefit.

The potential benefit was quantified based on lost saving opportunities. An example of a lost opportunity and impact analysis will be illustrated and explained using the following figures: Figure 45, Figure 46 and Figure 47. Presented in Figure 45 is the 24-hour profile of the CV of COG for the day of the impact analysis as measured by GA-2. As seen from this figure, the 24-hour profile commenced with a stable CV of COG profile. It was around hour 10:00 that a sudden change was experienced, where the CV of COG fluctuated drastically between 10, 17 and 25 MJ/Nm^3.

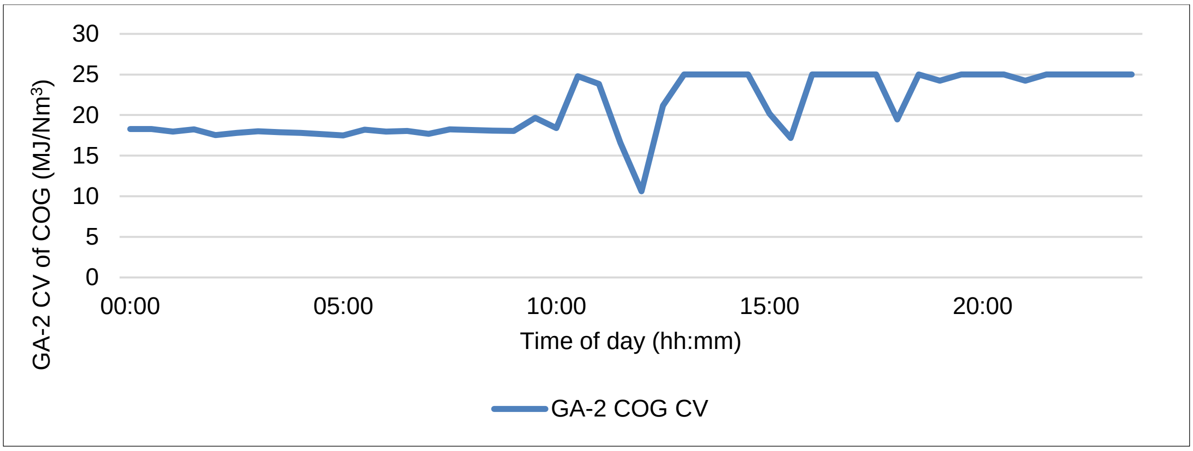

Figure 45: GA-2 CV of COG for impact analysis

The resulting impacts of the CV of COG changes on the furnace temperature are presented in Figure 46. The various furnace zones have been assigned various colourings for ease of differentiation. The solid lines present the temperature set points of the zones, while the fragmented lines show the temperature readings. All the furnace zones were combusting COG, except the THZ, which was using natural gas.

The effects of the drastic CV of COG fluctuations are seen in the fluctuations of the temperatures of the zones using COG. The temperatures deviated from the set-points by varying degrees. With a set-point of 1 250 °C, the PHZ showed significant deviations. The BHZ, ESZ and WSZ have temperature set-points of 1 300 °C. These zones also show visible fluctuations and deviations from the set-point. The THZ was using natural gas, hence minimum fluctuations and deviations from the set-point.

Importantly, it can be seen that all the zone temperatures deviate by decreasing. As indicated in earlier sections, readings of 10 and 25 MJ/Nm^3 from GA-2 indicate unavailable CV of COG data. Figure 45 shows these readings. The unavailable CV of COG data results in difficulties in controlling the temperature. Therefore, the furnace operators applied the trial-and-error method to adjust the air-fuel ratio and keep the furnace stable. This shows the significant impact of the air-fuel ratio.

Excess or insufficient air-fuel ratio have the same impact of decreasing the furnace temperature. The excess air absorbs the available heat from combustion, which decreases the temperature. Excess fuel, due to insufficient air, also absorb the available heat produced from the combustion, subsequently decreasing the final temperature of the furnace.

A significant difference in the performance of the ESZ and WSZ is visible. These zones have the same capacity and number of burners. However, they portray a different performance output, as shown in Figure 46. The WSZ did not show major deviations from the set point, compared to the ESZ. This shows the significance of considering the actual current performance of the furnace zones when performing air-fuel ratio adjustments.

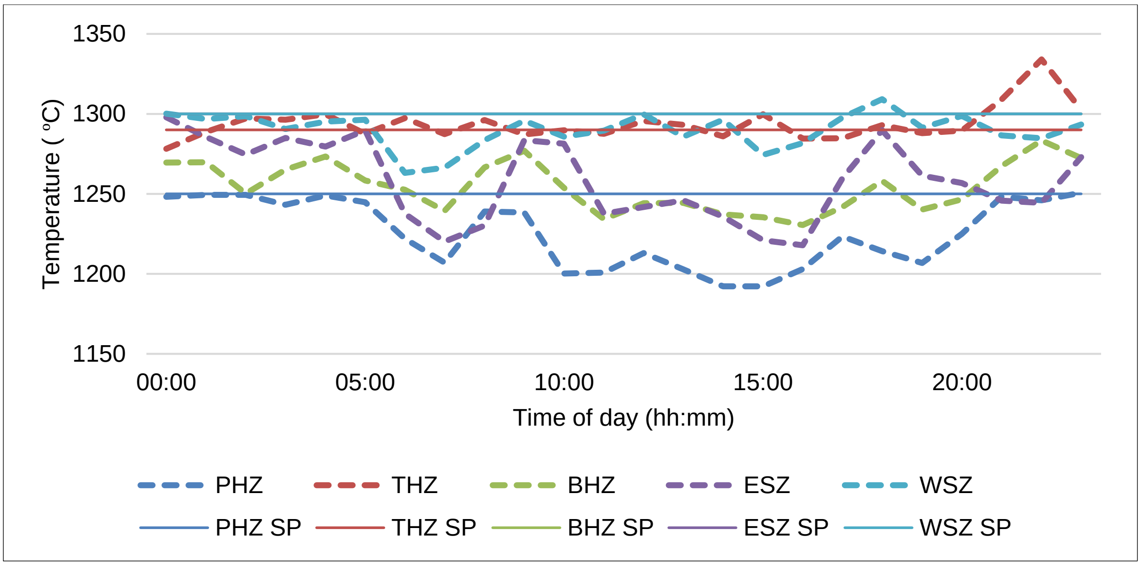

Figure 46: Furnace zones temperature profiles

The decrease in furnace temperatures has adverse impacts on the furnace energy usage and the resulting production figures. The impact on energy usage and production for the present illustration is presented in Figure 47. A general increase in energy intensity with time was identified. This is an indication of energy use inefficiency. It can also be seen that at hour 18:00, a production output of 0 tonnes was experienced, while the furnace continued to consume 226 GJ of energy.

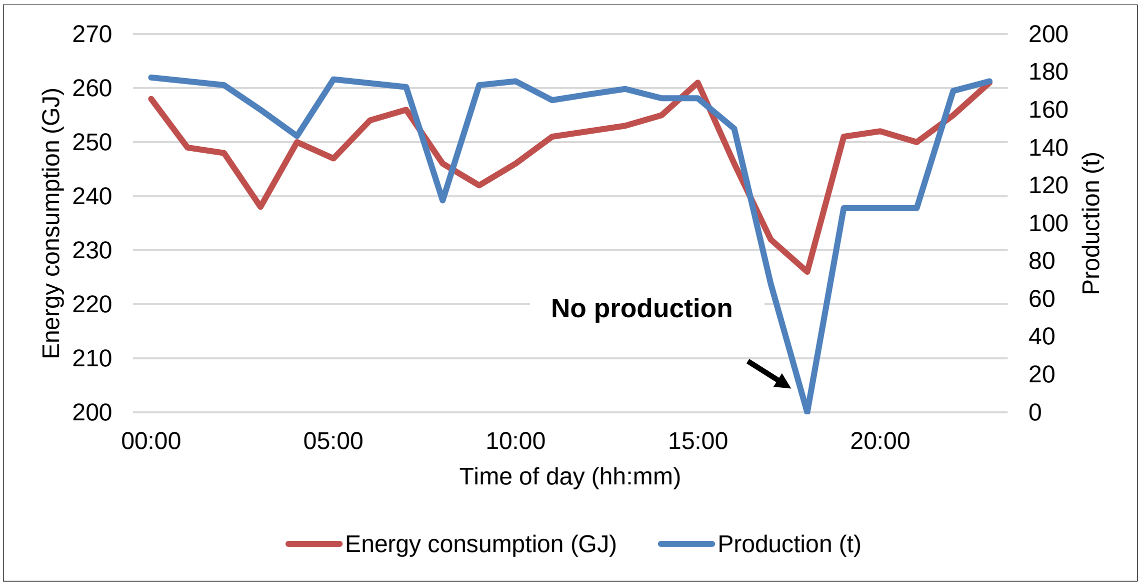

Figure 47: Furnace energy consumption as a function of production

The lost opportunity benefit was quantified on the energy wastage i.e. energy consumption without the required production output. There were 519 instances of energy saving lost opportunities identified for the given baseline period. Energy wastage at the furnace occurs as a result of normal operation disruptions. The main disruptions were identified and grouped as profile changes, unplanned maintenance, plant breakdowns and cold furnace occurrences. The groups and their contributions toward the 519 instances are presented in Figure 48.

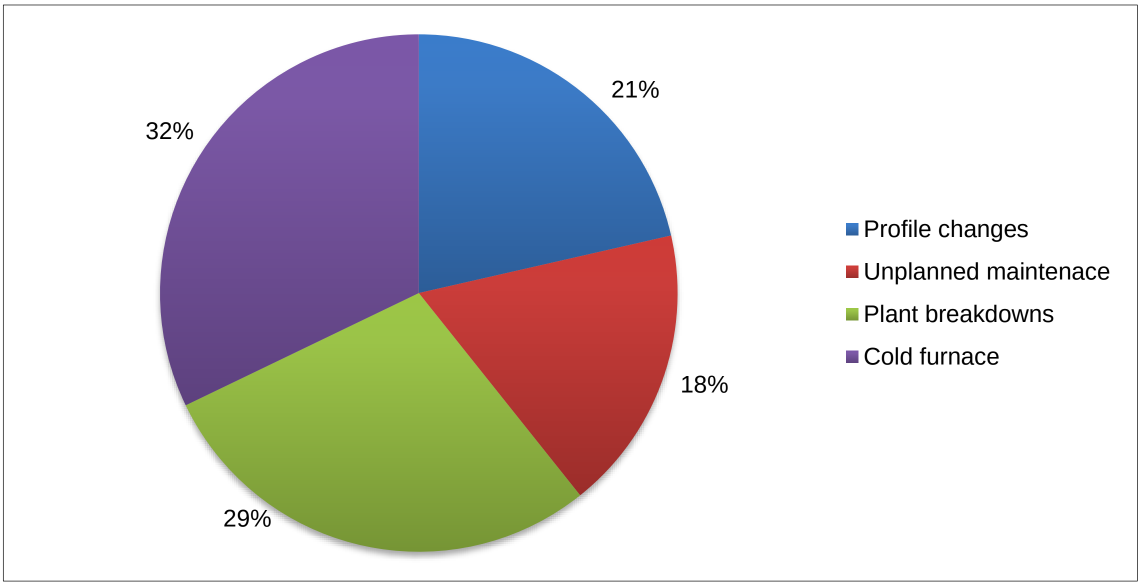

Figure 48: Normal furnace operation disruptions

The cost benefit for this study was determined based on cold furnaces instances due to the poor performance of COG combustion processes. The quantified lost benefit was extrapolated over a year. A total loss 53 000 GJ of energy was determined. Using the most recent published natural gas maximum price of R 141/GJ [21], the prevention of these losses translates to an estimated potential saving of R 7,5 million/annum.

Additional savings benefit based on steel production losses are possible. When furnace temperatures are not sustained, deviations from production plans and targets are experienced. The number of rejects increases, which can either be returned to the yard to be recharged into the furnace or discarded as scrap steel. The resulting impact is increased production costs. However, the monetary impact due to production losses could not be quantified due to the confidential nature of steel products market pricing by individual manufacturing companies.

3.5 Conclusion

This chapter of the study serves to verify the solution methodologies developed in Chapter 2 and validate the results thereof. The first methodology was developed for the determination of the appropriate air-fuel ratio for COG combustion in the respective furnace zones. This was verified theoretically using simulations with actual furnace data. Validation of the results was done through a practical application on a billet mill reheating furnace of Plant A. The practical results showed a 2 – 5 % error from the theoretical application outcomes. The theoretical and practical deviations will be used as a basis upon which the future work recommendations for this study will be formulated.

The second was a novel methodology for determining the unknown CV of COG. Three different methods were developed. The verification of these methods showed a 98 % accuracy in determining the unknown CV of COG when compared to actual plant data. The benefit of the solution was quantified based on lost opportunities for energy savings. Using the natural gas maximum price of R 141/ GJ, a potential annual saving of R 7,5 million can be realised for Plant A reheating furnace.

4 CONCLUSION AND RECOMMENDATIONS

Reheated billet in hot rolling in a process [24]

[24] World Steel Association [BE], [Online] Available: steeluniversity.org. Accessed: 2019-03-08

4.1 Preamble

This chapter summarises and concludes this study. A brief summary of the study will be given. The identified study problem, the research objectives formulated towards the solution development and the resulting novel contributions will be reviewed. The limitations of this study will be identified and discussed, followed by recommendations for further work to improve on the current study and its contribution to literature and industry.

4.2 Summary of the study

The identified problem was that the South African steel manufacturing industry is under financial pressure. Reduced production output and exports, increased imports combined with continuously increasing energy and operational costs have adversely affected the profitability of the domestic market. Energy use contributes 20 – 40 % towards operational costs. For the local sector, this energy is contributed to by coal (34 %), electricity (36 %) and natural gas (30 %). Coal reduction is limited as it is a production raw material, while extensive studies on electricity reduction have already been done.

This study focused on the need for natural gas consumption reduction for energy savings. The improved and maximised usage of alternative energy sources can contribute to energy reduction. Process by-product gases carry 18 % of the energy input. Coke oven gas was identified to be the most competitive with natural gas and compatible with high-temperature requirement applications, such as in steel reheating furnaces. Reheating furnaces consume 70 % of the energy of hot-rolling milling processes.

The utilisation of by-product gas is accompanied by challenges such as fluctuating supply and calorific value, as well as uncleanliness. These adversely affect combustion processes. Previous studies on by-product gas utilisation for energy efficiency in steelworks and reheating furnaces were discussed and reviewed. The purpose was to identify available methods to improve coke oven gas utilisation in steel reheating furnaces, which were reviewed against identified criteria. The outcomes of the review and the shortcomings led to the formulation of the study objectives and identification of three novel contributions.

The main objective of this study was to enable increased usage of coke oven gas in steel reheating furnaces. An adaptive method for combustion air-fuel ratio adjustments with fluctuating coke oven gas calorific value was identified as required. Unclean coke oven gas clogs gas-analysing equipment, hindering the time-continuous quantification of the energy content of the fuel gas. A reliable method for calorific value estimations was a required comprehensive part of this work.

A model for determination of the air-fuel ratio was developed. The aim was to eliminate the use of trial-and-error methods by furnace operators to adjust the air-fuel ratio for furnace stability maintenance. The model was verified through simulations that studied the effects of the changing calorific value and air-fuel ratio on the furnace zone temperatures. A new control philosophy was then developed. Three different methods were also developed for the time-continuous estimation of the calorific value of coke oven gas. These were verified using actual plant data. The estimation methods showed a maximum accuracy of 98 %.

The results of the simulations were validated on a case study (Plant A). The implementation results showed deviations of 2 % – 6 % in the furnace temperature values compared to the theoretical application values obtained through simulations. This is considered as an indication that the developed method successfully achieved the set objectives. The results of the practical application showed that steel facilities could potentially reduce the annual cost of natural gas by R 7,5 million.

The cost of energy is a burden to the South African industrial sector. Great efforts and investments have been put in place to research alternative and sustainable sources of energy. Production processes produce fuel gases as by-products. The effective utilisation of these fuel gases can improve the energy performance of facilities. For use in combustion processes, the appropriate air-fuel ratio adjustments will ensure maximum liberation of the energy content of the fuel. The developed model serves as a reliable tool for changes in the quality of combustion fuels.

4.3 Novel contributions evaluation

In Section 1.4 of this study, the study objectives were given. The completion of this study was able to address the enlisted objectives as follows:

- Literature sources were reviewed for existing measures used for improved by-product gas utilisation, and outcomes were evaluated.
- Relevant methods and approaches were adapted from literature for the development of a generic and functional adaptive air-fuel ratio determination methodology for various CVs of COG and furnace operating conditions.
- A new and simplified control philosophy for use by furnace operators to adjust air-fuel ratios was developed.
- A novel methodology to estimate the unknown CV of COG was developed.
- The impact of CV fluctuations and the corresponding air-fuel ratio on the furnace temperature was simulated.

- Practical tests for the validation of the air-fuel ratio methodology on a steel reheating furnace case study were undertaken.
- The natural gas-saving cost benefit of the developed solution was quantified.

From the addressed study objectives, the novel contributions of the study were formulated and discussed in Section 1.5. This section addresses the relevance of the novel contributions of the study.

Novel contribution 1:

An adopted method for adaptive air-fuel ratio adjustments for steel reheating furnace temperature zones, based on the calorific value of coke oven gas and the current operating conditions of the respective zones.

A review of literature sources discusses various measures usable for improved by-product gas utilisation. In combustion processes, the appropriate air-fuel ratio is critical for the maximum release of the energy content of the fuel. Some steel facilities are equipped with gas analysers for the measurement of the CV of COG, which also provide the ideal, stoichiometric combustion air-fuel ratio in furnaces. The actual air-fuel ratio differs from the ideal due to variations in energy performance of furnace zones, burner capacity, and allowable fuel gas and air flowrate. Existing methods for combustion air-fuel ratio determination were adapted for improved combustion control of COG in steel reheating furnaces according to the CV of COG and the current operating conditions of the reheating furnace. The developed study solution is adaptable for similar industrial challenges.

Novel contribution 2:

A unique and newly developed control philosophy for use by furnace operating personnel with less knowledge and expertise to make informed decisions for air-fuel ratio adjustments, instead of using the trial-and-error method.

By-product gases fluctuate in supply and CV. The literature survey indicated an extensive focus on the management, optimal distribution and scheduling of by-product gases to address the fluctuating supply. CV of COG fluctuations give is to combustion control challenges due to the need to continually adjust the air-fuel ratio. Drastic COG fluctuation events cause malfunctions to the furnace built-in control system, whereby the furnace operators are required to override the system and manually adjust the air-fuel ratio. This is typically done using a trial-and-error method, the success of which depends on the expertise and experience of the operator. A novel control philosophy is developed for an informed decision-making procedure for operators with less knowledge and expertise to adjust the air-fuel ratio.

Novel contribution 3:

Development of a new generic and integrated producer-to-user solution approach to estimating the unknown calorific value of coke oven gas in integrated steel manufacturing facilities.

The calorific value of a fuel is a measure of its energy content and it is vital for the effective management and utilisation of the fuel. Gas analysers are used for measuring the CV of coke oven gas on steelworks. However, the impurities contained in COG clog the analysers. Reheating furnaces in continuous operations require continuously available and reliable CV data of the COG for efficient control of combustion processes. A novel integrated producer-to-user methodology for time-continuous CV estimations of COG is developed.

4.4 Limitations and recommendations for future work

The aim of this study was to provide a reliable method to improve the usage of COG in steel reheating furnaces. The focus was on the control of combustion processes using integrated steel facility-produced COG, which has a fluctuating CV. Proper combustion control results in reduced furnace temperature fluctuations.

The study had two main sub-sections, i.e. the estimation of unknown CV of COG and an improved utilisation of COG. Steel facilities typically install gas analysers for CV of COG measurement. However, these are limited and unreliable due to their susceptibility to clogs from the gas impurities. This study identified the need to accurately quantify the calorific value of COG as the by-product gas with the highest energy content. Three different methods were developed.

Method 1 used the composition of the charged coal blends and the operating conditions of the coking process to estimate the CV of COG. The verification of the results showed that the lack of reliable data resulted in a poor correlation coefficient (CC) of 0.471, thus giving inaccurate

CV estimates. Factors such as environmental conditions, that affect the coking process due to air leakages, may affect the CV of the output COG.

This study recommends an evaluation of the extent to which these factors may affect the accurate estimation of the CV of COG by Method 1. Also, the determination of the CV of COG through reaction kinetics studies of the coke making process. The reaction kinetic studies will help determine the rate at which the volatile matter and carbon cracking reactions occur, incorporating mass and energy balance studies. These studies may potentially result in more accurate estimations and offer a reliable tool for verifying and validating other CV of COG estimation methods.

Method 2 considered the effect of the presence of a buffer in the COG supply network. The properties of the inlet COG can be used to estimate the CV of the outlet COG, and vice versa. This method gave a good CC of 0.961, which indicated that the method can be used as a reliable estimation method for CV of COG. Method 3 used the composition and operating conditions of the products of combustion.

Method 3 resulted in a CC of 0.794. This method will provide fairly good estimations of the CV of COG. However, there is a need for improvement. This study recommends the development of a similar estimation method that will consider other factors such as the latent heat of condensation of water vapour. The effects that such factors have of the CV of COG should be assessed and implemented to improve the CV estimations.

The second major section of the study involved the adjustment of air-fuel ratio in the combustion of COG with fluctuating CV. The effects of the fluctuating CV of COG and the corresponding air-fuel ratio were modelled and simulated. The simulated models were validated in a practical study on a steel reheating furnace. The simulated and actual temperature values were shown to have an average error within 2 % - 6%. Two major sources of the cause of the deviations from accurate furnace temperature predictions were identified as thermal coupling and energy loss. Studies to quantify and account for the effects of these factors and thus improve the control of COG combustion processes are recommended.

4.5 Conclusion

A need to improve by-product gas utilisation in steel milling operations was identified. This is for the dire need to reduce the cost of energy for South African steel producers to improve competitiveness. Coal, electricity and natural gas are the main energy sources used for the sector. A potential for reducing natural gas consumption lies in the improved usage of coke oven gas due to its similar combustion characteristics. However, the use of coke oven gas is associated with combustion process challenges.

A model to determine the appropriate combustion air-fuel ratio in steel reheating furnace zones was developed. The theoretical and practical application of this model proved to be effective. The impurities in coke oven gas clog gas-analysing equipment for calorific value measurements, which again affects combustion processes. A method to estimate the unknown calorific value of coke oven gas was developed and verified. Verification of the method showed a 98 % accuracy. Therefore, the developed methodology addressed the identified problem and achieved the formulated objectives of the study.

5 REFERENCES

[1] World Steel Association, “World steel in figures 2019,” worldsteel.org, Belgium, 2019.

[2] World Steel Association, “World steel in figures 2018,” worldsteel.org, Belgium, 2018.

[3] World Steel Association, “Steel Statistical Yearbook 2018,” worldsteel.org, Belgium, 2018.

[4] C. Van Deventer, “Developing an evaluation model for cost saving initiatives on sinter plants,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2018.

[5] G. H. Popescu, E. Nica, R. O. Ștefănescu-Mihăilă, and G. Lăzăroiu, “The United States (U.S.) steel import crisis and the global production overcapacity till 2016,” *Metalurgija*, vol. 55, pp. 538–540, 2016.

[6] W. J. J. Breytenbach, “Framework for operational changes to reduce electricity costs in the South African steel industry,” PhD Thesis, North-West University, Potchefstroom, South Africa, 2017.

[7] EYGM Limited, “Globalize or customize: finding the right balance. Global steel 2015–2016,” EGYM, Ltd, 2017.

[8] R. A. Dondofema, S. Matope, and G. Akdogan, “South African iron and steel industrial evolution: an industrial engineering perspective,” *South African Journal of Industrial Engineering*, vol. 28, pp. 103–113, 2017.

[9] S. G. J. Van Niekerk, “Improving energy cost performance of steel production mills,” PhD Thesis, North-West University, Potchefstroom, South Africa, 2018.

[10] T. P. Stewart, E. J. Drake, S. M. Bell, J. Wang, and R. E. Scott, “Surging steel imports put up to half a million U.S. jobs at risk,” Economic Policy Institute, Stewart and Stewart, Washington, D.C., 2014.

[11] R. Remus, M. A. A. Monsonet, S. Roudier, and L. D. Sancho, “Best available techniques (BAT) reference document for iron and steel production,” European Commission JRC Reference Report, Seville, Spain, 2013.

[12] A. Hasanbeigi, M. Arens, and L. Price, “Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction : A technical review,” *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 645–658, 2014.

[13] K. He and L. Wang, “A review of energy use and energy-efficient technologies for the iron and steel industry,” *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 1022–1039, 2017.

[14] J. M. Bermúdez, A. Arenillas, R. Luque, and J. A. Menéndez, “An overview of novel technologies to valorise coke oven gas surplus,” *Fuel Processing Technology*, vol. 110, pp. 150–159, 2013.

[15] B. Lu, G. Chen, D. Chen, and W. Yu, “An energy intensity optimization model for production system in iron and steel industry,” *Applied Thermal Engineering*, vol. 100, pp. 285–295, 2016.

[16] South African Department of Energy, “2018 South African energy sector report,” Department of Energy, Pretoria, 2018.

[17] W. J. J. Breytenbach, “Integration of electricity cost saving interventions on a water distribution utility,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2014.

[18] R. Maneschijn, J. C. Vosloo, and M. J. Mathews, “Investigating load shift potential through the use of off-gas holders on South African steel plants,” in *Proceedings of the 13th Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town*, 2016, pp. 104–111.

[19] South African Department of Energy, “South African coal sector report,” Department of Energy, Pretoria, 2018.

[20] South African Department of Energy, “2018 South African energy prices statistics,” Department of Energy, Pretoria, 2018.

[21] South African Department of Energy, “2018 energy price report,” Department of Energy, Pretoria, 2018.

[22] G. Khoele, “SASOL Gas application for approval of maximum gas prices in terms of section 21(1)(p) and approval of distinguishing features in terms of section 22(1) of the Gas Act, 2001 (ACT NO.48 of 2001) for the period 1 July 2017 to 30 September 2018,” Nersa, Sandton, South Africa, 2017.

[23] E. Worrell, L. Price, and N. Martin, “Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector,” *Energy*, vol. 26, pp. 513–536, 2001.

[24] International Energy Agency (IEA), “Tracking industrial energy efficiency and CO2 emissions,” OECD/IEA, Paris, France, 2007.

[25] S. G. J. Van Niekerk, “Quantification of energy consumption and production drivers in steel manufacturing plants,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2016.

[26] Minister of Finance, “Draft carbon tax bill,” Cape Town, pp. 1–65, 2017.

[27] RSA National Treasury, “Treasury tables carbon tax bill in parliament,” Cape Town, pp. 1–5, 2018.

[28] E. Schubert and R. Gottschling, “Co-generation: A challenge for furnace off-gas cleaning systems,” *Southern African Pyrometallurgy*, pp. 6–9, 2011.

[29] Y. Yang, K. Raipala, and L. Holappa, “Ironmaking,” *Treatise on Process Metallurgy*, vol. 3, pp. 2–88, 2014.

[30] X. Zhao, H. Bai, and J. Hao, “A review on the optimal scheduling of byproduct gases in steel making industry,” *Energy Procedia*, vol. 142, pp. 2852–2857, 2017.

[31] X. Zhang, J. Zhao, W. Wang, L. Cong, and W. Feng, “An optimal method for prediction and adjustment on byproduct gas holder in steel industry,” *Expert Systems with Applications*, vol. 38, pp. 4588–4599, 2011.

[32] S. Caillat, “Burners in the steel industry: Utilization of by-product combustion gases in reheating furnaces and annealing lines,” *Energy Procedia*, vol. 120, pp. 20–27, 2017.

[33] R. Razzaq, C. Li, and S. Zhang, “Coke oven gas: Availability, properties, purification, and utilization in China,” *Fuel*, vol. 113. pp. 287–299, 2013.

[34] A. Ludick, “Developing a by-product gas controller to improve on-site electricity generation for iron and steel manufacturing,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2018.

[35] P. Diemer, H. Killich, K. Knop, H. B. Lüngen, M. Reinke, and P. Schmöle, “Potentials for Utilization of Coke Oven Gas in Integrated Iron and Steel Works,” Espiriti Santo, Brazil, 2004.

[36] United States Environmental Protection Agency, “Compilation of Air Pollution Emission Factors, 5th ed.” 1995.

[37] V. Cuervo-Piñera *et al.*, “Blast furnace gas based combustion systems in steel reheating furnaces,” *Energy Procedia*, vol. 120, pp. 357–364, 2017.

[38] D. G. Schalles, “Efficient utilisation of steel mill by-product fuels for high temperature heating processes,” Pittsburg, PA, USA, 2007.

[39] S. Nomura and T. Nakagawa, “The yield of coke oven gas from hard and semi-soft coking coals,” *International Journal of Coal Geology*, vol. 168, pp. 179–185, 2016.

[40] A. Gonzalez Hernandez, L. Paoli, and J. M. Cullen, “How resource-efficient is the global steel industry?,” *Resources, Conservation and Recycling*, vol. 133, pp. 132–145, 2018.

[41] S. G. J. Van Niekerk, W. J. J. Breytenbach, and J. H. Marais, “Developing an optimisation model for industrial furnace gaseous fuel distribution for energy cost savings,” in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town*, 2017, pp. 38–41.

[42] United States Environmental Protection Agency, “Available and emerging technologies for reducing greenhouse gas emissions from the iron and steel industry,” U.S. Environmental Protection Agency (EPA), North Carolina, USA, 2012.

[43] X. M. Nguyen, F. Lawayeb, P. Rodriguez-Ayerbe, D. Dumur, and A. Mouchette, “Nonlinear model predictive control of steel slab walking-beam reheating furnace based on a numerical model,” in *2014 IEEE Conference on Control Applications (CCA 2014)*, 2014, pp. 191–196.

[44] B. Lu, D. Chen, G. Chen, and W. Yu, “An energy apportionment model for a reheating furnace in a hot rolling mill – A case study,” *Applied Thermal Engineering*, vol. 112, pp. 174–183, 2017.

[45] World Steel Association, “Energy use in the steel industry,” Brussels, Belgium, 2018.

[46] E. Worrell, P. Blinde, N. Maarten, E. Blomen, and E. Masanet, “Energy efficiency improvement and cost saving opportunities for the U.S. iron and steel industry: An ENERGY STAR guide for energy and plant managers,” Energy Analysis Department, Environmental Energy Technologies Division, University of California, Berkeley, CA, 2010.

[47] H. Mac Nulty, “Energy efficiency in the steel sector: Why it works well, but not always,” *Organisation for Economic Co-operation and Development (OECD/OCDE)*, 2015.

[48] A. Steinboeck, K. Graichen, and A. Kugi, “Dynamic optimization of a slab reheating furnace with consistent approximation of control variables,” *IEEE Transactions on Control Systems Technology*, vol. 19, pp. 1444–1456, 2011.

[49] M. Modesto and S. A. Nebra, “Exergoeconomic analysis of the power generation system using blast furnace and coke oven gas in a Brazilian steel mill,” *Applied Thermal Engineering*, vol. 29, pp. 2127–2136, 2009.

[50] B. Marais, “A framework for electricity generation opportunities in the South African integrated iron and steel industry : The ArcelorMittal Newcastle case,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2011.

[51] R. Murray and J. A. De Kock, “Potential in utilising furnace off-gas at a ferrochrome smelter with gas engines,” in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town*, 2015, pp. 171–177.

[52] R. Murray, “Utilizing waste energy from a submerged arc furnace at a ferrochrome smelter plant,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2015.

[53] P. v. Z. Venter, S. E. Terblanche, and M. van Eldik, “Improving power generation from fluctuating off-gas productions,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town*, 2015, pp. 225–231.

[54] A. F. Ryzhkov, E. I. Levin, P. S. Filippov, N. A. Abaimov, and S. I. Gordeev, “Making more efficient use of blast-furnace gas at Russian metallurgical plants,” *Metallurgist*, vol. 60, pp. 19–30, 2016.

[55] D. Pugh, A. P. Crayford, P. J. Bowen, T. O’Doherty, R. Marsh, and J. Steer, “Laminar flame speed and markstein length characterisation of steelworks gas blends,” *Applied Energy*, vol. 136, pp. 1026–1034, 2014.

[56] J. G. Wang *et al.*, "Soft-sensing method for optimizing combustion efficiency of reheating furnaces," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 73, pp. 112–122, 2017.

[57] H. S. O. Santos, P. E. M. Almeida, and R. T. N. Cardoso, "Fuel costs minimization on a steel billet reheating furnace using genetic algorithms," *Modelling and Simulation in Engineering*, vol. 2017, pp. 1–11, 2017.

[58] C. K. Tan, J. Jenkins, J. Ward, J. Broughton, and A. Heeley, "Zone modelling of the thermal performances of a large-scale bloom reheating furnace," *Applied Thermal Engineering*, vol. 50, pp. 1111–1118, 2013.

[59] Y. Hu, C. K. Tan, J. Broughton, P. A. Roach, and L. Varga, "Nonlinear dynamic simulation and control of large-scale reheating furnace operations using a zone method based model," *Applied Thermal Engineering*, vol. 135, pp. 41–53, 2018.

[60] N. Wang, Z. Wen, and F. Su, "Optimal heating and energy management for the reheating furnace using oxygen enhanced combustion," *Fundamental Research Funds for the Central Universities*, vol. 2, pp. 1–23, 2013.

[61] M. Jha and V. K. Singh, "Assessment of energy efficiency in reheating furnace of a steel plant by using process heating assessment and survey tool (PHAST)," *Recent Research in Science and Technology*, vol. 5, pp. 33–36, 2013.

[62] J. Sun, Y. Guo, and R. Gong, "Research on combustion control scheme optimization of steel rolling heating furnace," *2010 International Conference on Computer and Communication Technologies in Agriculture Engineering (CCTAE 2010)*, vol. 3, pp. 56–59, 2010.

[63] D. Chen, B. Lu, X. Zhang, F. Dai, G. Chen, and Y. Liu, "Fluctuation characteristic of billet region gas consumption in reheating furnace based on energy apportionment model," *Applied Thermal Engineering*, vol. 136, pp. 152–160, 2018.

[64] J. A. Swanepoel, "Modelling techniques to minimise operational costs in energy intensive industries," PhD Thesis, North-West University, Potchefstroom, South Africa, 2014.

[65] S. H. Han, Y. S. Lee, J. R. Cho, and K. H. Lee, "Efficiency analysis of air-fuel and oxy-fuel combustion in a reheating furnace," *International Journal of Heat and Mass Transfer*, vol. 121, pp. 1364–1370, 2018.

[66] Törnbom J., "System analysis for implementing preheated blast furnace gas and oxyfuel combustion in a steel reheating furnace at SSAB EMEA, Oxelösund," M. Sc. Dissertation, Luleå University of Technology, Oxelösund, Sweden, 2015.

[67] A. Steinboeck, D. Wild, and A. Kugi, "Energy-efficient control of continuous reheating furnaces," *IFAC Proceedings Volumes*, vol. 15, pp. 359–364, 2013.

[68] E. Kilinç *et al.*, “An energy efficiency analysis of an industrial reheating furnace and an implementation of efficiency enhancements methods,” *Energy Exploration & Exploitation*, vol. 32, pp. 989–1003, 2015.

[69] S. H. Han and D. Chang, “Radiative slab heating analysis for various fuel gas compositions in an axial-fired reheating furnace,” *International Journal of Heat and Mass Transfer*, vol. 55, pp. 4029–4036, 2012.

[70] S. Hosokai, K. Matsuoka, K. Kuramoto, and Y. Suzuki, “Modification of Dulong’s formula to estimate heating value of gas, liquid and solid fuels,” *Fuel Processing Technology*, vol. 152, pp. 399–405, 2016.

[71] L. Kong, L. Su, X. Zhou, L. Chen, and Q. Liu, “Accuracy guarantee for determining the calorific value for dual gas sources,” *Flow Measurement and Instrumentation*, vol. 65, pp. 233–239, 2019.

[72] A. Dale, C. Lythall, J. Aucott, and C. Sayer, “High precision calorimetry to determine the enthalpy of combustion of methane,” *Thermochimica Acta*, vol. 382, pp. 47–54, 2002.

[73] K. I. Wong and P. K. Wong, “Adaptive air-fuel ratio control of dual-injection engines under biofuel blends using extreme learning machine,” *Energy Conversion and Management*, vol. 165, pp. 66–75, 2018.

[74] S. Strommer, A. Steinboeck, C. Begle, M. Niederer, and A. Kugi, “Modeling and control of gas supply for burners in gas-fired industrial furnaces,” in *2014 IEEE Conference on Control Applications (CCA 2014)*, 2014, pp. 210–215.

[75] K. W. Cho *et al.*, “Premixed combustion of coke oven gas in a metallic fibre mat,” *Fuel*, vol. 80, pp. 1033–1036, 2001.

[76] M. B. Mampuru, M. Kleingeld, J. H. Van Laar, J. H. Marais, and S. G. J. Van Niekerk, “Improving By-product Gas Utilisation in Steel Milling Operations,” in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town - (In press)*, 2019.

[77] World Steel Association, “Steel industry co-products – worldsteel position paper,” worldsteel.org, Belgium, 2018.

[78] B. Das, S. Prakash, P. S. R. Reddy, and V. N. Misra, “An overview of utilization of slag and sludge from steel industries,” *Resources, Conservation and Recycling*, vol. 50, pp. 40–57, 2007.

[79] X. Zhao, H. Bai, and J. Hao, “A review on the optimal scheduling of byproduct gases in steel making industry,” in *Energy Procedia*, 2017, vol. 142, pp. 2852–2857.

[80] A. Steinboeck, D. Wild, and A. Kugi, “Nonlinear model predictive control of a continuous slab reheating furnace,” *Control Engineering Practice*, vol. 21, no. 4, pp. 495–508, 2013.

[81] C. Van Aarde, “A general approach to develop and assess models estimating coal energy content,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2018.

[82] K. Campbell, “A critical analysis of emission quantification methods in the ferrochrome industry,” PhD Thesis, North-West University, Potchefstroom, South Africa, 2018.

[83] S. G. J. Van Niekerk, J. C. Vosloo, and E. H. Mathews, “Practical quantification of coal energy consumption in large manufacturing industries for verifiable energy reporting and energy incentive applications,” in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE), Cape Town*, 2015, pp. 199–205.

[84] Z. Olinga, X. Xia, and X. Ye, “A cost-effective approach to handle measurement and verification uncertainties of energy savings,” *Energy*, vol. 141, pp. 1600–1609, 2017.

[85] L. Slupik, A. Fic, Z. Bulinski, A. J. Nowak, J. Smolka, and L. Kosyrczyk, “Sensitivity analysis of the computational model of the coal carbonisation process,” *Applied Thermal Engineering*, vol. 114, pp. 1002–1013, 2017.

[86] D. P. Ross, C. A. Heidenreich, and D. K. Zhang, “Devolatilisation times of coal particles in a fluidised-bed,” *Fuel*, vol. 79, pp. 873–883, 2000.

[87] R. M. Felder and R. W. Rousseau, *Elementary Principles of Chemical Processes*, Third., vol. 83, no. 1. Hoboken (NJ): John Wiley & Sons, Inc., 2005.

[88] R. Vesel and J. Isaacs, “Temperature setpoint optimization in steel reheat furnaces using open architecture neural network and modeling software,” in *AISTech - Iron and Steel Technology Conference Proceedings*, 2019, pp. 2940–2949.

[89] R. S. Van As, “An improved baseline model for a mine surface cooling plant DSM project,” M. Eng. Dissertation, North-West University, Potchefstroom, South Africa, 2017.

[90] W. Booysen, “Measurement and verification of industrial DSM projects,” PhD Thesis, North-West University, Potchefstroom, South Africa, 2014.

[91] B. B. Agrawal and A. S. Mathur, “New Ironmaking Processes : Relevance to India,” R&D Centre for Iron and Steel, Ranchi, India, 2011.

[92] A. Quiyoom, R. Golani, V. Singh, and V. V. Buwa, “Effect of differential flow schemes on gas-liquid flow and liquid phase mixing in a Basic Oxygen Furnace,” *Chemical Engineering Science*, vol. 170, pp. 777–789, 2017.

[93] R. Hu and C. Zhang, “Discussion on energy conservation strategies for steel industry: Based on a Chinese firm,” *Journal of Cleaner Production*, vol. 166, pp. 66–80, 2017.

[94] D. Kumar and D. Kumar, “Latest developments in the iron and steel industry,” *Management of Coking Coal Resources*, pp. 9–60, 2016.

[95] Asia Pacific Partnership for Clean Development and Climate, “The State-of-the-Art Clean Technologies (SOACT) for Steelmaking Handbook, 2nd Ed.,” Lawrence Berkeley National Laboratory, Bekerly, CA: American Iron and Steel Institute, Washington, DC, 2010.

[96] S. M. Zhuchkov *et al.*, “Ways of reducing energy costs in the continuous rolling of sections,” *Metallurgist*, vol. 48, pp. 174–180, 2004.

APPENDICES

Appendix A: Overview of the steel production stages

Sinter production

Sintering entails the physical and metallurgical preparation of the blast furnace burden. This improves permeability and reducibility during the production of molten iron. This step of burden preparation affords modern blast furnaces an improved performance. During sintering, fine ores, anthracite, additives and recycled iron-bearing materials are ignited in the presence of coke. The combustion releases heat, reaching temperatures of up to 1 480 °C [4], [36].

The high temperature causes surface melting and the material becomes agglomerated. The agglomeration is then crushed and screened. The screened oversize (> 9,5 mm) product fraction is sent to be cooled, and eventually to the blast furnace. The undersize (< 9,5 mm) is recycled to be reprocessed. Approximately 15 % of the energy expenditure of steel producing is accounted to sinter production [4], [11], [36].

Coke production

Coke is an important, high carbon-containing reductant of iron ore into molten iron through the blast furnace route. Metallurgical coke is produced from the carburisation of coking coal. The carburisation takes place inside coke ovens at temperatures above 1 000 °C in the absence of air [4], [36], [32], [85]. The process typically lasts for 15 – 20 hours [85].

More than 90% of coke produced in integrated steelworks is dedicated for use in the blast furnace. Coke also functions as the main source of fuel in the blast furnace. Other important functions of coke include burden support and being an active reducing agent. Coke production accounts for 0,75 – 2 GJ/t crude steel produced [4], [36], [32].

Ironmaking

Ironmaking involves the chemical reduction of iron-bearing material into molten iron, otherwise referred to as hot metal. The process commonly takes place through the blast furnace, direct or smelting reduction routes. Through the blast furnace route, iron-containing material i.e., coke, sinter and limestone, are introduced at the top of the furnace. Hot blast air and PCI are introduced at the tuyère level. PCI is used as an additional reducing agent and fuel source. Coal tar or oil can also be used as additional fuel sources [36].

The reaction of the carbon-based agents with the oxygen in the blast air produces heat, carbon monoxide (CO) and hydrogen (H_2) gases. The CO reduces the iron oxides by removing oxygen, while the heat melts the charge. The main products from the blast furnace are molten iron and slag. The molten iron exits the blast furnace at temperatures approximating 1 480 °C. The molten iron is typically composed of 4 – 5 % carbon (C) and some impurities. The molten iron is then taken to a basic oxygen furnace (BOF) via torpedoes for further refining. This stage typically consumes 13,0 – 14,1 GJ/t molten iron produced [11], [12].

Due the scarcity and high costs associated with coking coals for the blast furnace iron-making route, alternative technologies have been under exploration. The smelting reduction (SR) and direct reduction processes are available alternative iron-making routes. The former process uses non-coking coal [12], [91].

Smelting reduction deviates from the need for coke and sinter required in the blast furnace – basic oxygen furnace (BF – BOF) route. Direct reduction uses iron ore fines, thus reducing pollution. The latter process removes oxygen from the ore while in its solid state. Natural gas is a typical reducing agent for this technology. Using the MIDREX technology, 68,5 Mt of direct reduced iron (DRI) was produced in 2008 [12], [91].

Steelmaking

The steelmaking stage encompasses the refinement of the molten iron into steel of a specified quality and composition. Through oxidation, the molten iron gets stripped of C and other impurities [92]. The molten iron becomes decarburised to a typical carbon content of 0,4 - 0,01 % at this stage of production [13], [93].

Different routes exist for steel production worldwide. The common routes are blast furnace – basic oxygen furnace (BF-BOF), EAF, and open-hearth furnace (OHF) [11]. The process routes differ in their energy intensities. The energy intensities range between 19,8 – 31,2 GJ/t crude steel for the BF-BOF, and 9,1 – 12,5 GJ/t crude steel for the EAF. The energy resources and raw materials are similar. The BF - BOF and EAF routes dominate steel production globally [13], [93]. Shown in Figure 49 is the crude steel production share per route in 2017.

The BF – BOF process route is presently the most common steel production route in the world. This process accounted for 71 % crude steel production in 2017, as seen in Figure 49. The EAF route was used to produce 28 % during the same year. The OHF and other processes only contributed to a combined 1 % of the total crude steel produced [2]. He and Wang [13] indicated that the environmental and economic disadvantages, as well as the energy-intensive nature of the OHF renders its use less desirable.

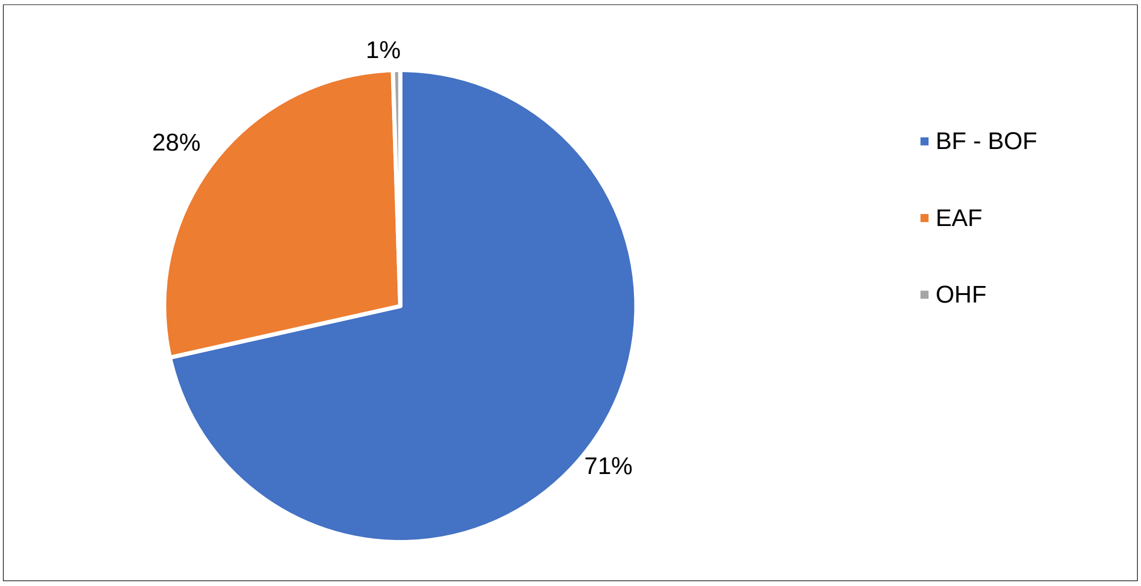

Figure 49: Crude steel production share by process in 2017. Taken from [2]

Major steel producers operate on integrated steel facilities, of which most use the BF – BOF route [94]. On the contrary, it has been argued that the EAF route promotes more cost savings and energy conservation than the BF - BOF route. Reduced emissions, low energy consumption and decreased fuel usage are some of the attractive attributes ascribed to the EAF route [93].

However, the EAF route cannot sustainably satisfy the growing demand for steel in isolation. This is due to the long product life cycle of steel products, owing to the strength and durability of steel. For instance, infrastructure made with steel lasts for 40 - 200 years. It was indicated that half the steel produced in 2050 will still be ore-based, i.e. via the BF – BOF route [40]. Thus, a combination of the BF - BOF and EAF production routes promote material input efficiency [45].

Steel finishing

For improved efficiency of downstream and upstream steel-making processes, steel may undergo ladle refining. At this stage, the steel is refined to the composition and quality as desired by the customer. Following suit is the continuous casting of steel. During the casting stage, molten steel gets solidified into blooms, billets or slabs for various industrial applications. The resulting casts are considered as semi-finished products [95].

Steel casts can further be subjected to a series of transformation operations. These include hot- or cold-rolling, forming, forging and finishing. During these operations, the thickness of the cast gets reduced while increasing the width and length. The surface properties of the casts are also improved. These operations are significant in that they impart important physical and chemical steel characteristics, such as the final shape and corrosion resistance, as desired by the customer [95], [46].

Appendix B: Best available practices in steel operations

Sinter production: Waste by-product gas heat recovery

This process minimises the volumes the produced by-product gases by 50 % – 60 %. This is done by having the entire sinter strand housed, waste by-product gases recycled to the sinter bed and using the energy from the CO content. Heat is recovered from the sinter cooler gases. Air heated by the sinter cooler is used for oxygen enrichment in the recycled by-product gases, instead of using fresh air. The sinter cooler heated air may also be applicable for ignition air preheating in the ignition hood [11], [13].

A plant fitted with a sintering by-product gas system and a suction area of 250 m^2 can acquire an estimated CAPEX in the order of $US 16 million. Reduced consumptions of ignition gas and coke up to 10 MJ/t and 2 – 5 kg/t sinter, respectively, are the estimated savings. Significant reductions in GHG emissions, by-product gas cleaning investment costs and operation costs are some of the important additional benefits [11], [13].

Coke production: Coal moisture control

Fuel consumption savings approximated at 0,3 GJ/t of product can be achieved by drying coke producing coal using waste heat from residual COG. Reduction in carbonisation heat requirements by 0,17 GJ/t of product have been indicated for a steel plant in Japan. Improvements in coke strength and productivity by 1,7 % and 10 %, respectively, have been realised. The identified plant incurred costs of $US 76,6/t of steel, with an estimated payback period of over 50 years [13], [42], [46].

Additional use of COG

Coke oven use approximately 40 % of the produced COG as fuel. The remaining COG fuels equipment with high energy requirements, such as reheating furnaces, boilers to produce steam to generate electricity on-site, pumps and fans, as well as for process heat requirements. The consumption of natural gas can be reduced through reduced flaring, and increased usage in combustion processes [13], [42], [46].

Non-recovery coke ovens

The non-recovery coking process entails recirculating and combusting process by-products in the coking ovens, including raw COG. Heat recovery and electricity cogeneration opportunities are thus presented. This technique eliminates the conventional coke ovens associated air emissions and water pollution resulting from the recovery of by-products. Hence, the need and the associated costs for COG and wastewater treatment plants are eliminated [42].

Variable-speed drive (VSD) COG compressors

During the coking process, the generation of COG occurs at low pressures. Transportation of the gas within the internal gas grid requires that the gas gets pressurised. The energy required for gas compression can be reduced via the use of variable speed drive COG compressors. The use of VSD COG compressors provide the additional benefit of gas flow variability compensation due to coking reactions. A steel facility in The Netherlands realised energy savings of 0,006 – 0,008 GJ/t of coke on a VSD system that cost $US 0,47/t. A payback period of 21 years was estimated [42].

Ironmaking – blast furnace: Injection of COG and basic oxygen furnace gas (BOFG)

The injection of COG and BOFG can lead to a reduced consumption of coke by the blast furnace. Due to their low carbon content compared to coke, reductions in CO_2 emissions are also achieved. However, the thermochemical conditions of the blast furnace impose restricting limits of the volume of COG injectable at the tuyère level. The specified limit is 0,1 t COG/t hot metal. At the maximum injection setting, coke consumption is reduced by 0,98 t/t COG [46].

Recovery of BFG

When the blast furnace gets charged with burden, 1,5 % of the BFG escapes. A furnace in The Netherlands installed a BFG recovery system costing $US 0,47/t of hot metal. Approximately 17 kWh/t hot metal in energy savings have been realised, with an estimated payback period of 2,3 years [42].

Recuperator hot-blast stove

Energy from fuel savings in the range of 0,080 – 0,085 GJ/t hot metal can be realised through preheating blast furnace combustion air with hot-blast by-product gases. Meanwhile, combustion air preheating alone saves 0,35 GJ/t hot metal. The potential energy savings equate to cost savings between $US 18 – 20. Heat consumption reductions of 0,126 GJ/t hot metal by a medium type waste heat recovery device that recovered 40 – 50 % sensible heat from the gases has been reported. Upon implementation of this system, payback is estimated to be realised after 8,7 years [11]

Recycling of BFG

Blast furnace performance can be improved through recycling of BFG, which contains CO and H_2 as iron reducing gases. Additionally, CO_2 emissions are reduced while the utilisation of C and H_2 is enhanced. However, this technology has not been commercially established previously. Intensive research and development on this topic is underway in the Ultra-Low CO_2 Steelmaking program [23]

Steelmaking - Basic oxygen furnace: Basic oxygen furnace gas and sensible heat recovery

The removal of carbon from steel by blowing oxygen into the BOF forms CO, the energy containing component of BOFG. The BOFG exits the furnace at temperatures in the range 1 650 – 1 900 °C. Recovery of BOFG and its associated heat is deemed the most beneficial technology for energy saving improvements in steelmaking. Heat recovered from BOFG is predominantly used for boiler applications. BOFG and BFG can alternatively be applied in gas turbine-combined cycle units for power production. Thermal efficiency can also be increase by using BOFG as fuel [13]. The recovery process can potential save energy estimated to be in the range of 0,53 – 0,92 GJ/t. The capital costs are estimated at $US 34,4/t of steel, with an estimated payback time of 12 years [13], [42], [46].

Steelmaking – Electric arc furnace: By-product gas post-combustion

The by-product gas from the steel bath in the EAF contains CO and H_2. Utilising the chemical energy contained in these gases through post-combustion can reduce electricity requirements, while increasing production. The energy from the post-combustion can be used to preheat scraps from 300 – 800 °C or to heat the EAF ladle steel. Oxygen and fuel injection are further optimised through post-combustion of the by-product gas. A typical post-combustion system can save 6 – 11 % on electricity and 3 – 11 % reduction in tap-to-tap time. These savings are dependent on operational conditions. Information on the costs and payback time of this system is unavailable [13], [23], [42], [46].

Steel hot rolling milling operations: Proper reheating temperature

Reheating semi-finished products in the furnace prior to rolling consumes fuel energy in the range of 1,30 – 1,65 GJ/t finished product. Unit fuel consumption reduction by 9 – 10 % can be realised by reducing the heating temperature by 100 °C [96]. However, this technology has an overall energy consumption increase impact. The rolling forces and moments increase, while increasing wear on mill equipment. It was suggested that varying the reheating temperature should be considered following a systems approach [23].

Avoid overloading of reheating furnace

Overly ambitious production goals may lead to the tendency to overload the furnace. An overloaded furnace tends to become cold, which may be compensated by artificially high temperature settings. This results in higher than normal firing rates by the burners. Eventually, increased gas volumes, poor heat transfer and excessively high stack temperatures are experienced. Increased heat losses and fuel consumption are thus inevitable [42], [46].

Hot charging

Reheating furnaces can realise energy savings by charging steel at temperatures elevated above ambient [46]. The feasibility of this practice depends on the layout of the plant. It is beneficial and favourable that the caster and reheating furnace are in proximity to each other. This is for the mitigation of a long, hot connection pathway. However, energy savings can be offset by interruptions from either the caster or rolling mill. Hence, a production schedule that balances yard stock and hot charging must be in place to maintain energy savings [42].

Introduction of the hot charging practice on a plant requires investment costs estimated to be $US 23,5/t of hot rolled steel. A furnace charging steel at 700 °C can save energy up to 0,6 GJ/t of hot charged steel, with payback estimated after 5,9 years. These energy savings are, however, plant dependent [13], [42], [46].

Process control in hot strip mill

Improved productivity, reduced product rejects and reduced downtime lead to indirect energy savings. This can be achieved through improved process control in the mill. Controlled furnace oxygen levels and combustion air fans VSDs optimise the combustion process. Energy savings achieved through this measure are dependent on the furnace load factor and the applied control strategies, since the furnace load is time variable [42].

Arcelormittal's Sidmar plant (Belgium) reduced rejects and downtime by 87 % and 88 %, respectively, through installing this system. Reduced rejects gave rise to energy savings approximated at 0,3 GJ/t of product. A Belgium plant with a production capacity of 3,1 Mt invested $US 3,6 million and had payback time of 1,2 years [42].

Recuperative burners

A recuperator recovers and transfers heat from outgoing process exhaust gases to incoming combustion air. The heat is utilised in recuperative burners. Fuel consumption can be reduced by 10 – 20 % in a furnace fitted with a recuperative burner system compared to one without. Chinese furnaces with burners using BFG and COG mixtures have been shown to achieve energy savings of up to 34 % more compared to traditional reheating furnaces [46].

Replacing aging burners with newer designs significantly increases the efficiency and heat recovery, while lowering NOx emissions. Energy savings approximated at 0,7 GJ/t of product can be realised. A recuperative burner system may require an estimated $US 3,9/t of product in investment costs. The payback for a recuperative burner system is expected after 1,8 years [46].

Flameless burners

Preheating combustion air is an extensively applied technique to enhance the efficiency of reheating furnaces. However, this practise is used with limitations due to the paralleled increase in NOx emissions. Flameless burner technology is an alternative measure. Flameless air-fuel and oxy-fuel burners use air and oxygen, respectively, as oxidisers. Combustion is carried out using internal flue gas recirculation in the presence of diluted oxygen conditions. High thermal efficiency, reduced fuel consumption, better thermal uniformity and higher levels of heat flux are important advantages that flameless oxy-fuel has over conventional oxy-fuel [13].

Furnace insulation

Heat loss through furnace walls can be reduced by using ceramic low-thermal mass insulating materials in the place of conventional insulators. Applying coatings can lead to higher savings. Insulating a furnace in continuous operation can lead to energy savings estimated as 0,16 GJ/t of product. Capex for implementing this technology estimated at $US 15,6/t product, with an associated payback period estimate of 31 years [13], [42], [46].

Walking beam furnace

Installation of a walking beam furnace with a state-of-the-art combustion control at WCI Steel reduced electricity usage by 25 %/t of product. An overall fuel consumption reduction by 37,5 %/t of product was realised in comparison to three pusher-type furnaces [42].

Heat recovery to the product

When slabs cannot be hot-charged directly from the caster, energy can be recovered from high temperature process exhaust gases brought into contact with relatively cooler slabs. Thus, the slabs get preheated. Furnace charge preheated to 450 – 550 °C using exhaust gases led to 32 % in cost savings for North Start Steel. Charging semi-finished products at 650 °C and 980 °C reduced unit energy consumption by 50 % and 70 – 80 %, respectively [13], [23], [46].

Waste heat recovery from cooling water

Lower-pressure steam can be produced from waste heat recovered from hot strip mill cooling water. Savings in energy are approximated to be 0,03 GJ/t of product. However, electricity consumption increases by 0,0006 GJ/t of product. Implementing this technology requires $US 1,3/t of product in investment costs. Increased expenditure by $US 0,11/t of product incurred from operating and maintenance is estimated. A payback time of more than 50 years is projected [42].

Oxygen levels control and VSDs on combustion fans

Combustion in the furnace can be optimised through oxygen level control and installation of VSDs on combustion fans. This ensures that excess air remains at a minimum to avoid large volumes of generated waste gases. Installing VSDs can reduce fuel consumption by 0,33GJ/t of product. The investment costs may amount to approximately $US 0,79/t of product, and an estimated payback period of 0,8 years [42], [46].