

Developing a by-product gas controller to improve on-site electricity generation for iron and steel manufacturing

A Ludick



orcid.org 0000-0001-5842-3936

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Supervisor:

Dr J. H. Marais

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Student number: 29901677

Abstract

Title: Developing a by-product gas controller to improve on-site electricity generation for iron and steel manufacturing

Author: Alexander Ludick

Supervisor: Dr J. H. Marais

Keywords: Blast furnace gas, Cost reduction, Energy, Energy saving, Flare reduction, Iron and steel industry, Gas holder, Gas holder utilisation

High production costs and low demands have placed the South African iron and steel manufacturing industry under severe pressure. The steel manufacturing industry is therefore forced to streamline internal structures and reduce production costs as a means to ensure sustainable operations.

Electricity is the second largest energy source used in iron and steel manufacturing. A typical South African steel producing plant consumes in the vicinity of 960 MWh over 24 hours. South African industrial electricity tariffs increased by 250% additional to inflation from 2003 to 2016. Historical electricity tariff trends and Eskom's allegations to future tariff increases projects that electricity rates have not yet stabilised.

The iron and steel making process produces combustible gases. These gases are recovered as a by-product and used for fuel at different stages in iron and steel manufacturing. By-product gases are also used to generate electricity through the on-site power generation plant. The gas distribution network is kept safe by flaring excess by-product gas.

Day-to-day imbalances in the production and consumption of by-product gases are responsible for a significant portion of flaring. Addressing control of these imbalances will reduce flaring of by-product gases. Up to 550 TJ of energy is lost annually due to by-product gas flaring on a South African iron and steel manufacturing facility.

The combination of iron and steel manufacturing being electricity intensive and South African electricity tariffs ever increasing led to the objective of this study. The objective of the study is to decrease electricity expenditure by increasing on-site power generation. Improving

by-product gas utilisation increases on-site power generation. Increasing on-site power generation reduces electricity expenditure.

A human operator, additional to several other responsibilities, reactively controls the by-product gas networks. Manual control is complicated, labour intense and requires constant concentration. The demanding complexities of the system accompanying many parameters lead to the operators frequently missing electricity generation opportunities.

In this study, a methodology is developed to improve by-product gas utilisation. A controller is the mechanism responsible for the improved by-product gas utilisation. The controller continuously determines the electricity generation rate according to the by-product gas availability. The proposed controller uses instantaneous gas holder levels to determine the available by-product gas.

The methodology and control proved valid after a case study was implemented. The control was incorporated into the Supervisory Control and Data Acquisition (SCADA) system. Inputs from plant personnel refined the control. Complexities led to a comprehensive Measurement and Verification (M&V) study. The results from the case study proved that the controller could reduce flaring by 20%.

A control benefit of more than R4.8 million per annum was determined. A project sustainability strategy concludes the study. The strategy revolves around continual awareness of the control performance. An automated reporting system was used to generate and distribute reports among relevant parties.

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Nomenclature

Abbreviations

BAT	Best Available Technology
BC	Before Christ
BFG	Blast Furnace Gas
BOF	Basic Oxygen Furnace
BOS	Basic Oxygen Steelmaking
BOSG	Basic Oxygen Steelmaking Gas
CAPEX	Capital Expenditure
CAS-OB	Composition Adjustment by sealed Argon Bubbling-Oxygen Blowing
COG	Coke Oven Gas
CPI	Consumer Price Index
CV	Calorific Value
DSM	Demand Side Management
EAF	Electric Arc Furnace
ESN	Eco State Network
ET	Electricity Tariffs
FTP	File Transfer Protocol
GUI	Graphical User Interface
HFO	Heavy Fuel Oil
ID	Induced Draft
IEA	International Energy Agency
ISCOR	Iron and Steel Industrial Corporation
KPI	Key Performance Indicator
LP	Linear Programming
LSSVR	Least Squares Support Vector Regression
M&V	Measurement and Verification
OPC	OLE for Process Control
MILP	Mixed Integer Linear Programming
MKL	Multiple Kernel Learning
PA	Project Assessment
PDCA	Plan to Check Act
PI	Proportional Integral
SCADA	Supervisory Control and Data Acquisition
TOU	Time of Use
WI	Wobbe Index

Symbols

AE_E	Alternators electricity generation energy consumption	[GJ]
AE_G	Alternator electricity generation	[MW]/[MWh]
ALT_{SP}	Alternators set point	[MW]
BM_{AF}	Baseline model adjustment factor	
BM_{RA}	Baseline model routine adjustment	
BS_E	Boilers steam generation energy consumption	[GJ]
BS_S	Boilers steam generation	[tonne steam/h]
c	Y-intercept	
C_{AS}	Eskom affordability subsidy constant	[R/MWh]
C_{ERSC}	Eskom electrification and rural subsidy charge	[R/MWh]
CB	Controller benefit	[MWh]/[GJ]
ER	Electricity rate	[R/MWh]
ET	Eskom electricity tariff	[R/MWh]
f	Flow of gas	[m ³ /h]
FS_E	By-product gas energy flared by plant	[GJ]
$FS_{reduction}$	By-product gas flaring reduction factor	[%]
GHL	Gas holder level	[%]
m	Gradient	
N_A	Number of alternators	
N_B	Number of boilers	
N_{FS}	Number of flare stacks	
WET	Weighted electricity tariff	[R/MWh]
WI	Wobbe index	[GJ/m ³]
η_{Ak}	Alternators combined efficiency	[tonne steam/MWh]
η_B	Boilers combined efficiency	[GJ/tonne steam]

Subscripts

ACI	After controller implementation
BCI	Before controller implementation
BP	Baseline period
cap_a	Additional capacity
cap_{max}	Maximum capacity
$cap_{utilised}$	Capacity utilised
D	Day type; weekday, Saturday or Sunday
HH	High-high
i	Flare stack number; 1, 2, ..., N_{FS}
j	Boiler number; 1, 2, ..., N_B
k	Alternator number; 1, 2, ..., N_A
LL	Low-low
max	Maximum

<i>min</i>	Minimum
<i>sim</i>	Control active simulated
<i>TOU</i>	Time of use; peak, standard or off-peak
Δt	Period

Superscripts

<i>F</i>	By-product gas; COG or BFG	$[m^3/h]$
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Unit of measure

<i>GJ</i>	Gigajoule
<i>h</i>	Hour
<i>kPa</i>	Kilopascal
<i>kW</i>	Kilowatt
<i>kWh</i>	Kilowatt-hour
m^3	Cubic meter
<i>MJ</i>	Megajoule
<i>MW</i>	Megawatt
<i>MWh</i>	Megawatt-hour
<i>PJ</i>	Petajoule
<i>R</i>	Rand
<i>TJ</i>	Terajoule
<i>tonne</i>	Metric unit of mass equal to 1000 kilograms
%	Percentage

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Chapter 1 – Background



Figure 1: Silhouette of two blast furnaces¹

The need for a by-product gas controller

¹ Financial Tribune, “IMIDPRO’s output rises”, [Online]. Available:
www.financialtribune.com/articles/economy-business-and-markets/68651/imidro-s-output-rises

1.1 Introduction

In Chapter 1, the needs and objectives of the study are developed. Background of the South African iron and steel manufacturing industry reveals the current challenges faced. A brief overview of the iron and steel manufacturing process serves as a platform for a comprehensive overview of by-product gas in iron and steel manufacturing. The needs and study objectives address the problem statement.

1.2 Challenges faced by the South African iron and steel industry

The South African iron and steel manufacturing industry is under pressure due to high production costs and low steel demands [1]. The industry is forced to re-evaluate current production strategies and streamline internal structures [2]. Additionally, the South African government realises the importance of the sector to the economy and is supporting the industry [3]. These measures include safeguarding the local steel market from cheaper imports from countries like China [4]. Understanding the origin of the South African iron and steel manufacturing industry assists to understand its current condition and challenges.

In 1928, South Africa established the Iron and Steel Industrial Corporation (ISCOR) as a state company. ISCOR intended to produce steel and create employment. Production started in 1934 and then increased shortly after this due to war-time demands forcing the industry to expand. Numerous expansions in the sector led to ISCOR establishing its third fully integrated steelworks in 1969 [5].

The worldwide recession, during 1970's to 1980's, resulted in a reduction of the local steel market. Additional to the local difficulties, a world oversupply at the time rendered export prices to uneconomic levels. ISCOR reacted by early closure of older, less efficient facilities. By the end of the 1980's, the South African government transferred ISCOR to the private sector [5].

Current high steel production costs are partially due to the period of the industry erection. The South African power generation sector had positive prospects during 1960 – 1979 [6], [7], forecasting stable electricity tariff growth. Thus energy was of little concern during this period. This resulted in the South African iron and steel industry not being established with an energy-conscious focus.

In recent times, the South African electricity tariffs have unfortunately increased with more than 8% compared to global leading countries [8]. During the 2000's South African electricity rates experienced a drastic spike. The increase in electricity rates was and still is due to Eskom suffering a shortage of capital and skills, internal mismanagement, lack of capacity, recurrent delays, and maintenance backlogs [9]–[12].

In Figure 1, the average electricity tariff for each sector including agriculture, residential, commercial, traction, mining, local authorities, industrial, and international are compared. Industrial electricity tariffs increased from 14c/kWh to 63c/kWh which is 350% and inflation based on Consumer Price Index (CPI) by 100% from 2003 to 2016 [13], [14]. Considering that the electricity rates have consistently increased 12.5% annually from 2010 to 2016, the electricity tariffs have not yet stabilised and will continue to grow at this rate.

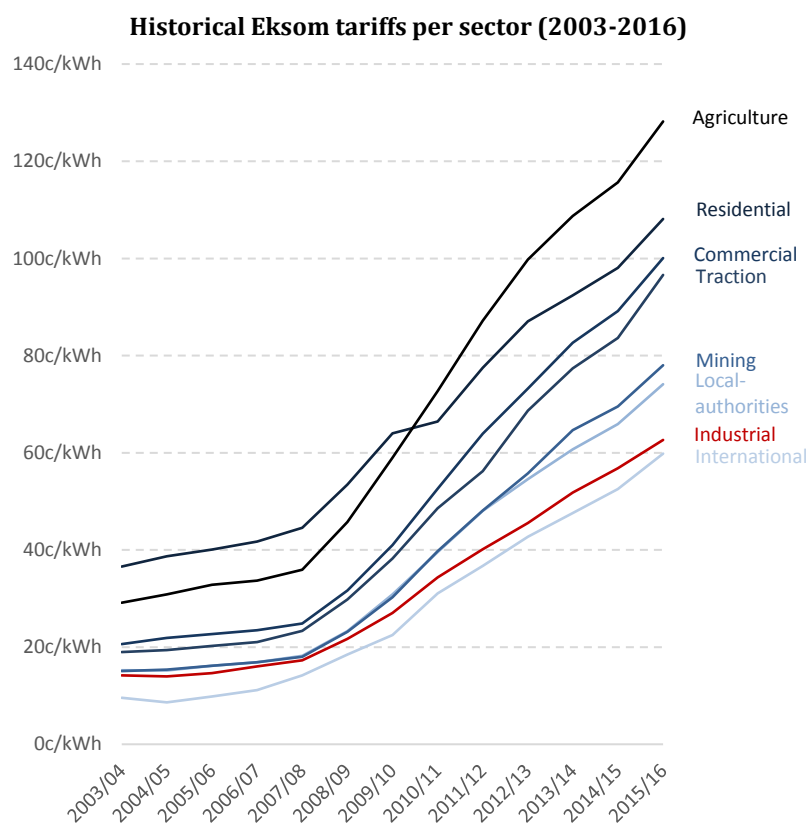


Figure 1: Average Eskom electricity tariffs per sector from 2003 to 2016 [13]

The high electricity tariffs provided by Eskom plays a significant role in the South African iron and steel manufacturing industries tribulation. A typical steel manufacturing plant can require up to 40MW to function. Second to coal, electricity is responsible for the largest portion of energy costs on South African steel manufacturing institution [15].

Iron and steel manufacturing is a specialised process consisting of various components. It is essential to understand the principle elements in the iron and steel manufacturing in order to understand and realise how electricity costs can be reduced.

1.3 Overview of iron and steel manufacturing process

Steel originated in the 13th century when a blacksmith discovered that iron, commonly used at the time, became progressively harder if left in a charcoal furnace. Since then, breakthroughs in steel manufacturing followed periodically throughout the decades. Wars and self-proclaimed inventors acted as catalysts in the progression of steel [16].

The first step in modern iron and steel manufacturing is iron. Iron is produced using a blast furnace [17]. Raw inputs including iron ore, coke and lime are melted in the blast furnace and air are added to supply the combustion process with oxygen [18]. Liquid iron emerges from the blast furnace which still contains between 4% – 4.5% carbon among other impurities rendering it brittle [19].

Iron is then converted into steel by either the Basic Oxygen Steelmaking (BOS) or Electric Arc Furnace (EAF) process [20]. In the BOS process, molten iron and recycled steel are combined and injected with high temperature and high purity oxygen, reducing the carbon content to between 0% – 1.5% [21]. Whereas in the EAF process, recycled steel is melted using electric arcs converting the recycled steel into high-quality steel [22].

After the steel has been formed, it is treated in its molten form to tweak the composition to a desired state. The compositions are adjusted by adding or removing elements, controlling the temperature and production environment [23]. Some processes used to tweak the steel grade include stirring, a ladle furnace [24], ladle injection, degassing and Composition Adjustment by Sealed Argon Bubbling – Oxygen Blowing (CAS-OB) [25].

Continuous casters are used to cast and cut the molten steel strands into finite sections. Slabs, blooms or billets are formed with the casters depending on the final desired profile. The steel is then shaped in mills where it is rolled and formed into a desired shape and surface quality is reached [26].

The final condition and form of steel is generally dependent on the client who buys the raw product from the steel manufacturer. These alterations can consist of either one or a combination of the following: manufacturing, fabrication, and finishing consisting of shaping, machining, joining, coating, heat treatment and surfacing [27], [28].

The overview of the iron and steel manufacturing process serves as the necessary background to understand how the by-product gas forms part of the steel making process. It is a brief overview due to the study focusing on the utilisation of the by-product gas. A comprehensive overview of by-product gas in the iron and steel industry is provided in the following section.

1.4 By-product gas distribution and use in iron and steel manufacturing

During the iron and steel manufacturing process, several gases are produced. Some of these gases have flammable properties and therefore it can be used as fuel on the plant. Gases which are deemed as economical to reclaim and distributed across the plant can be used as by-product gases [29].

The three by-product gases typically used in the iron and steel manufacturing industry include, (1) Coke Oven Gas (COG), (2) Blast Furnace Gas (BFG), and (3) Basic Oxygen Steelmaking Gas (BOSG). COG is produced during the coke making process, BFG is generated during the iron making process, and BOSG is generated during the steel making process [29]–[31].

In Figure 2, the gas network including the cogeneration section is illustrated holistically. The gas network is broken up into three sections; gas supply, gas management and plant consumption, and steam supply and cogeneration. In the gas supply section, the three different plants which produce a by-product is shown namely; coke ovens, blast furnace and Basic Oxygen Furnace (BOF). Additionally, natural gas is listed under gas supply as it is used when the by-product gas in the system is not sufficient [32], [33].

Natural gas is generally sourced from an external supplier and bought on demand. It is, therefore, an additional expense per volume gas, unlike by-product gas which is considered free in this respect [33]. However, most plants determine costs to maintain the by-product gas network, therefore establishing a rate for the by-product gases. This is a method to benchmark how economical the by-product gas is to the facility.

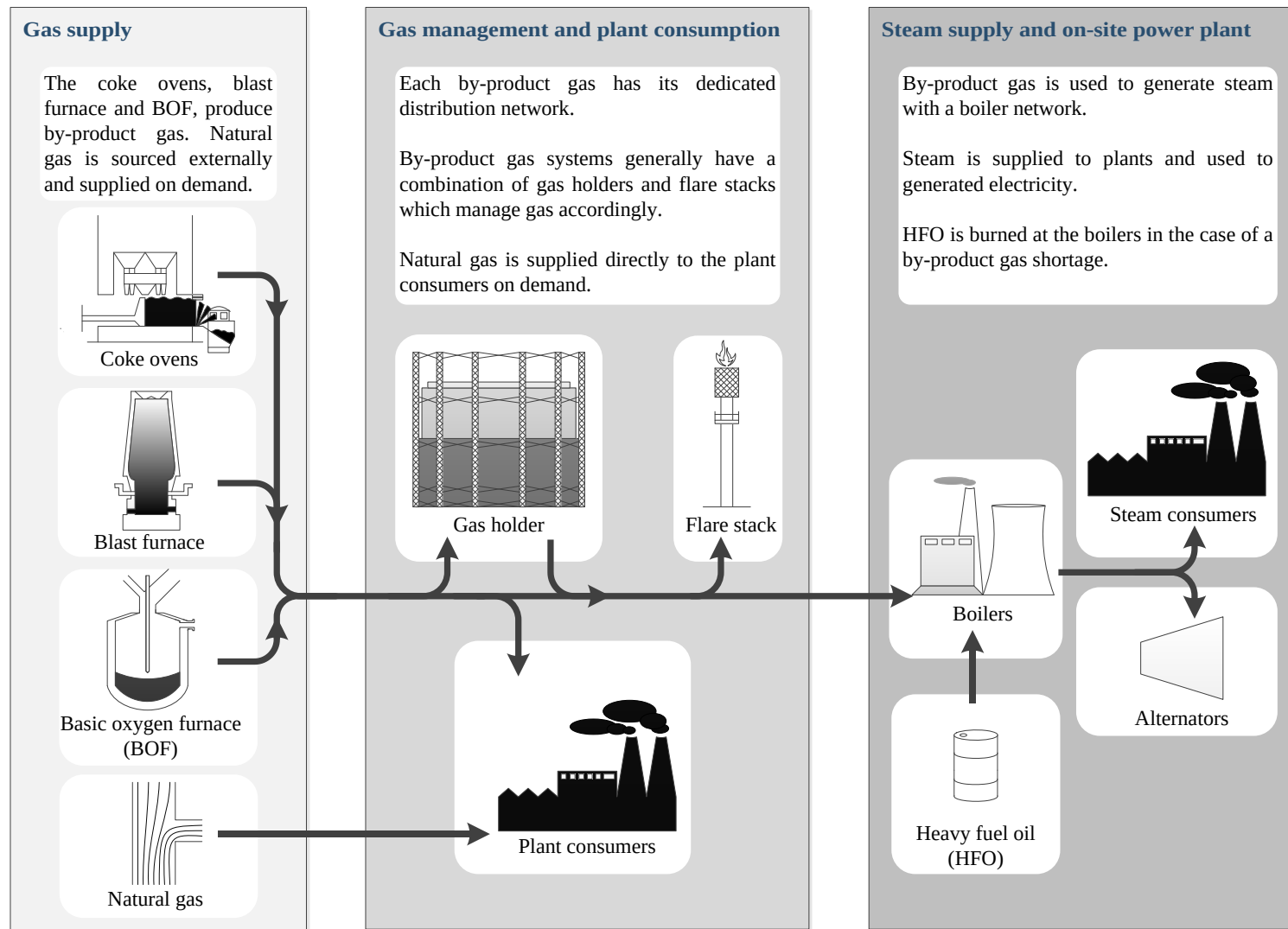


Figure 2: By-product gas distribution network for iron and steel manufacturing

Factors such as the gas quality influences the cost of the gas. After COG is produced, it contains impurities such as naphthalene and tar. These impurities clog pipes and burners up resulting in high maintenance costs and poor performance. It is therefore essential to clean COG gas right after it is produced [34].

In the gas management and plant consumption section (Figure 2), it is illustrated that the by-product gas is flowing as a single unit with an optional, in- or outflow to the gas holder, and inflow to flare stack and inflow to the plant consumers. The by-product gas consumers typically include a sinter plant, the blast furnace stoves, coke ovens, mills reheating furnaces, etc. Both the blast furnace and coke ovens produce and consume by-product gas [35].

Gas holders are used as a buffer in the gas network. A buffer is required as imbalances exist between by-product gas product and consumption. The gas holders used have a constant pressure but variable volume. This ensures that the system is always within the designed pressure range, even when the volume of gas inside the system fluctuates [32]. For example, if the amount of gas produced is more than consumed, the gas holder level will rise as the surplus gas flows into the holder. If the amount of gas produced is too little for the consumers, the gas holder level will drop as the shortage of gas flows to the consumers.

Instances exist where the amount of gas within the system is just too much. This means that the gas holder level has reached its upper-level limit and the amount of gas produced has no consumer to supply. In these instances, the by-product gas is flared. Gas distribution networks have flare stacks to relieve the network of too much gas [32].

After the gas management and plant consumption section, the by-product gas is distributed to the steam supply and the on-site power generation plant. As with the by-product gas consumers, there are consumers on the plant which require steam. The steam is generated by boilers preferably using by-product gas as the fuel [30].

When by-product gas is insufficient or unavailable for the boilers, Heavy Fuel Oil (HFO) is supplied. HFO is only used as a last resort due to its high price. There is generally an excess of by-product gas production justifying the need for an on-site power generation plant. The excess by-product gas is burned in the boilers to generate additional steam for the alternators to produce electricity for the plant [30].

Each by-product gas network is unique to a facility. The type of gas network varies depending on factors such as what method is used to produce the steel, how large the blast furnace is, how many mills there are, etc. The by-product gas network is unique to each facility depending on what was economically feasible for the plant.

1.5 Problem definition

Imbalances between the production and consumption of by-product gases exist due to manufacturing variations, equipment failures, shutdowns and control discontinuities. These difficulties combined with many other plant processes make it difficult for a single operator to control optimally and utilise the by-product gas efficiently.

Poor utilisation of by-product gas can lead to a significant economic loss. For example, a BOS iron and steel manufacturing facility with the capacity to produce two million tonnes of steel annually can provide by-product gas worth R115 000 /h. In other words, if the plant is unable to actively and efficiently utilise the by-product gas, it flares the by-product gas producing CO₂ emissions while having to buy additional gas as an energy source.

A full plant Mixed Integer Linear Programming (MILP) solution was developed for a case study. The solution was, however, rejected by the case study due to control constraints and a lack of reliable measurements on the plant side. A need for a simplified control solution existed to aid the operator to improve by-product gas utilisation. The control needed to be robust and function with the minimum amount of inputs.

1.6 Study objectives

The objectives of the study are to:

- Complete a comprehensive literature review concerning iron and steel manufacturing by-product gas networks, gas control and flare minimisation;
- Develop an iron and steel by-product gas controller;
- Simulate the developed controller;
- Implement the developed controller on an iron and steel manufacturing facility;
- Measure the impact of the controller on the facility; and
- Ensure that the control is sustainable.

1.7 Overview of dissertation

Chapter 1 – The introductory chapter introduces iron and steel’s (1) current industry status in South Africa, (2) manufacturing process, and (3) by-product gas distribution network. From the evaluation of current control used for the by-product. The need for this study as well as the study objectives were identified.

Chapter 2 – Within Chapter 2, a comprehensive literature review was completed. Literature concerning the objective of this study was reviewed section by section. Energy efficiency initiatives done on iron and steel producing facilities provide background on what efficiency strategies are currently being used.

Both the topics of by-product gas optimisation as well as previous work done on gas holders are critical to understanding what types of models are available and how efficient they are. Finally, the chapter is concluded on project performance quantification and sustainability, to ensure proper maintenance after implementation.

Chapter 3 – The methodology and controller developed to meet the study objectives are discussed in Chapter 3. Each step followed is explained in chronological order. Methods are suggested to implement, improve and track the performance after implementation.

Chapter 4 – The proposed methodology and controller are applied to a case study. Each step of the methodology developed in Chapter 3 is followed and the controller is tailored for the case study presented.

Chapter 5 – In Chapter 5, the conclusions of the study are discussed and recommendations are made for future work.

1.8 Conclusion

The challenges faced by the South African iron and steel manufacturing industry can be somewhat relieved by reducing the amount of electricity consumed by Eskom. It is due to iron and steel production being electricity intensive, and a typical South African steel producer requires 40 MW for day to day operation. Additionally, Eskom electricity tariffs have increased drastically in recent years, and trends show no signs of stabilisation.

Most iron and steel manufacturers have on-site electricity generation plants. These plants are preferably driven by by-product gas produced on separate stages during the iron and steel manufacturing process. Proper utilisation of the by-product gas is a difficult task assigned to a single process controller. The difficulties of the by-product gas network lie in the imbalances produced by the production and consumption demand of by-product gas.

Much work has been done on this matter, but the solutions' complicity require far too much reliable data from the facilities side. The South African iron and steel manufacturing facilities require a simplified by-product gas controller. The controller needs to be able to operate using minimum plant inputs and relieve the process controller's responsibility to monitor and manually adjust the by-product gas distribution network regularly.

This study focuses on the development of such a by-product gas controller based on a combination of work that has been done from the literature and the requirements for the South African industry. Additionally, the study needs to provide a measuring method to quantify the actual impact of the controller and a project sustainability strategy.

Chapter 2 – Literature review

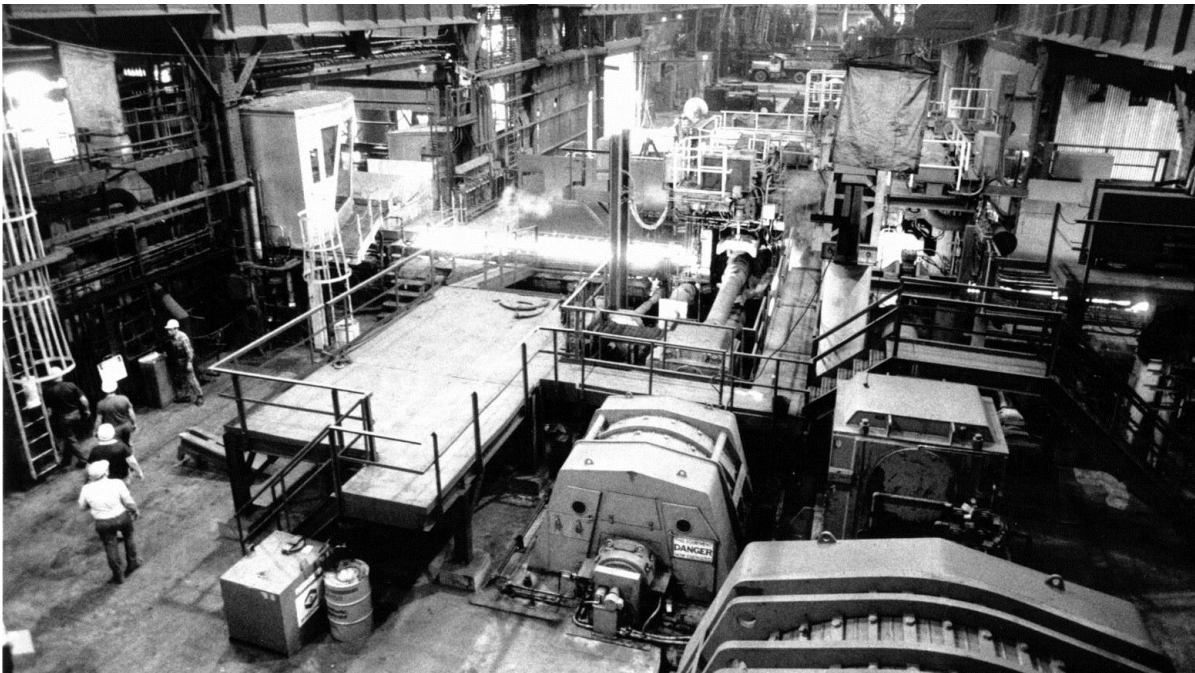


Figure 3: Inside a steel plant²

Previous work done

² The Morning Call, “Pictures: Historic photos of the Bethlehem steel plant”, [Online]. Available: www.mcall.com/news/mc-pictures-historic-photos-of-the-bethlehem-steel-plant-20151210-photogallery.html

2.1 Introduction

Chapter 2 consists of the literature review. The literature review is conducted over a variety of topic areas to assist in achieving the study's objectives. The literature review is done by focusing on what has been done in previous work, how it was done, the gap in the work if applicable, and how the work can contribute towards this study.

Previous work done consisting of any efficiency initiatives on iron and steel facilities provides a broad overview of the iron and steel manufacturing industry. The overview renders the required background for the specific topics regarding by-product gas optimisation and existing gas holder control models. All the objectives are realised after work on energy expenditure tracking and project sustainability is reviewed.

2.2 Existing efficiency initiatives on iron and steel facilities

2.2.1 General overview

Iron and steel manufacturing is regarded as a high energy intensive process. In 2012, steel manufacturing was responsible for 5% of all primary energy produced and 7% of all CO₂ emissions globally [36]. Projections indicate that by 2020 the GJ/t would reach a turning point and the sector's production efficiency would start increasing globally [37]. Due to the energy intensiveness of steel manufacturing, a lot of attention has been invested in improving the energy efficiency of this process.

According to the world steel association [38], improvements in the energy efficiency have led to 60% of energy efficiency from 1960 to 2014. Even though much progress has been made in the iron and steel manufacturing industry, the International Energy Agency (IEA) still projects that an approximate 20% of energy can be reduced by applying Best Available Technology (BAT) [39].

China currently holds the largest share of more than 50% of the global steel market, largely due to government support [40]. The iron and steel industry is, however, except for China, relatively evenly distributed across the world. Regionally specific energy saving potential studies have been conducted in China [41], Taiwan [42], USA [43], Germany [44], India [45], Europe [46], and Mexico [47].

These regional energy saving's studies are broad and extensive, some evaluated more than 30 different energy saving measures. These studies agree that BAT has the potential to have a significant impact in energy saving on the steel industry. More importantly, the significance of by-product gas recovery and management were highlighted in most of the studies.

The South African steel industry is lacking such a broad energy conservation study. Breytenbach [15] who developed a framework to reduce electricity cost expenditure in the South African iron and steel industry did more focused studies. The study focused only on electricity cost reductions, for example, load shift on large fans at energy plant.

The study revealed that electricity was the second largest cost contributor on South African steel plants. It does, therefore, indicate that any electricity cost reduction is of great value. The study conducted in this paper focuses on reducing by-product gas flaring by increasing on-site electricity generation. Thus, electricity consumption of the plant will not reduce holistically, however, the amount of electricity sourced from outside the facility will be reduced.

In the global iron and steel industry, much work is currently being done to reduce production energy intensity. Projections indicate that a global reduction in energy per crude tonne steel is expected. Currently, the South African iron and steel industry need regional specific energy saving development and improvements. The following section focuses on various energy saving initiatives.

2.2.2 Identified initiatives

A more in-depth review of the types of initiatives has to be done to understand the current direction of the research field, the type of energy saving projects and their adjacent impact. Currently, more than 150 iron and steel sector-specific energy improvement procedures and technologies exist [48].

The aim of the study is essentially to improve by-product gas utilisation by producing more on-site electricity generation. Thus, from the 150 initiatives identified [48] only the ones involved with fuel gas will be reviewed. The energy conservation initiatives are grouped according to plant/section on the facility as sinter and pelletizing, coke making process, blast furnace process, BOF process, EAF process, the casting process, rolling process, and general energy saving opportunities.

In Table 1, energy saving initiatives regarding gas control, waste fuel recovery, and on-site power generation is listed according to the appropriate plant/section in steel manufacturing process.

Section	Energy saving initiative	Study
Sinter and pelletizing	Use of waste fuels in the sinter plant, selective waste gas recycling and low emission and energy optimised	[49], [50], [51]
Coke making process	Programmed heating, automation and process control system and COG recovery	[49], [52], [53]
Blast furnace process	Recovery of BFG, hot blast stove automation	[49], [54], [55]
BOF process	BOFG recovery, BOFG sensible heat recovery	[52], [56], [57]
EAF process	EAF gas waste heat recovery	[58]
Casting process	N/A	-
Rolling process	Regenerative burners for reheating furnaces	[59], [60]
General	Energy monitoring and management system, high efficiency gas separation plant, gas turbine pilot fuel alternative technologies, by-product gas boiler power generation technology	[61], [62], [63],[64], [30]

Table 1: Iron and steel manufacturing sector-specific energy saving initiatives

The gas distribution network interlinks most of the sections with one another. Thus the energy saving initiatives involving by-product gas ranges relatively evenly across the sections. Some of the initiatives are Capital Expenditure (CAPEX) intensive such as gas turbine pilot fuel alternative [64] where others require little or no CAPEX at all, such as the automated control initiatives, [49],[61].

According to the identified energy saving initiatives, the by-product gas needs to be reclaimed. Automation of by-product gas handling would prove more energy efficient. Heat can be reclaimed from post production by-product gases. The final energy saving opportunity is to utilise the product gas at the consumer as efficiently as possible.

2.2.3 Contributions of general energy efficiency initiatives towards this study

As the review of the work above suggests, there is sufficient BAT available to reduce energy in the iron and steel manufacturing industry. The problem, however, is that the BATs' high rate of change, lack of knowledge and CAPEX in the steel industry of South Africa results in few of these technologies being implemented.

Steel producing facilities in South Africa have a significant gap. Most energy saving initiatives require either little or no CAPEX to implement. At most, the payback period of such an initiative needs be less than a year after implementation. Implementing a more efficient by-product gas controller falls between the specified boundaries.

The current research done of by-product gas, as highlighted in Table 1, accommodates any work done on utilisation of by-product gas. A significant amount of initiatives involve the reclamation of by-product gas. These initiatives make more by-product gas available for distribution and utilisation studies, similar to the controller presented in this study.

2.3 By-product gas optimisation

2.3.1 By-product gas, natural gas and HFO properties

This study revolves around by-product gas utilisation. Understanding the different properties and characteristics of each by-product fuel gas and substitutes are required to optimise the gas network. The properties and characteristics of each gas differs due to how the gas is formed.

The chemical properties, Wobbe Index (WI), and production rates of the by-product gases are summarised in Table 2. COG is the by-product gas with the highest energy content per volume. The WI of COG can be up to 650% and 250% higher than BFG and BOSG respectively [48]. Therefore, according to energy content, the priority needs to be firstly, the utilisation of COG followed by BOSG and then BFG.

In the case of production rates, BFG can be produced by 450% and 2250% more quickly than that of COG and BOSG respectively. This is by comparison of gas produced per tonne of product at the adjacent plant. On a conventional iron and steel manufacturing plant, the most considerable portion of the by-product distribution belongs to BFG. However, due to low

energy content, BFG is generally enriched with either natural gas or COG to sustain proper combustion [65].

Gas type	Chemical composition	Wobbe index (WI) [MJ/m ³]	Production rate
BFG	Hydrogen (H ₂) ~ 4% Carbon monoxide (CO) ~ 25% Carbon dioxide (CO ₂) ~ 20% Nitrogen (N ₂) ~ 51%	3 – 3.8	1400 – 1800 m ³ /tonne of liquid iron
COG	Organic chains (C _n H _m) ~ 0.1%-3% Oxygen (O ₂) ~ 0.1%-4%; Carbon dioxide (CO ₂) ~ 2%-5%; Carbon monoxide (CO) ~ 5%-10%; Methane (CH ₄) ~ 20%-30%; Hydrogen (H ₂) ~ 45%-64%;	16 – 19.3	400 – 450 m ³ /tonne of coke
BOSG	Hydrogen (H ₂) ~ <=1.5% Oxygen (O ₂) ~ <=2% Nitrogen (N ₂) ~ 10%-20% Carbon dioxide (CO ₂) ~ 15%-20% Carbon monoxide (CO) ~ 60%-70%	7.5 – 8	80 – 100 m ³ /tonne of liquid steel

Table 2: By-product gas properties [48]

Cuervo-Piñera et al. [65] conducted a study based in Europe with the objective to enhance BFG usage in reheating furnaces. The project was successful in developing burner technologies such as dual regenerative air fuel, oxy-fuel and flat-flame burners for 100% BFG use. Validation of the project on a case study proved reliable and safe operation during long-term testing.

Substitute fuels are used if by-product gas production is unable to meet the demand of the plant consumers. Natural gas substitutes the by-product gas for the typical plant. The boilers are the general exception where natural gas is not used to substitute the by-product gas. The substitute fuel used at the boilers is HFO [30].

In Table 3, the chemical compositions and WI for the natural gas and HFO is summarised. The WI index for HFO is significantly more than natural gas. It is important to note that HFO is specified as a dense fluid where natural gas is specified as a considerably less dense gas. The use of these fuels is avoided, where possible, due to additional fees compared to free on-site by-product gas which is produced [31].

Fuel type	Chemical composition	Wobbe index (WI) [MJ/m ³]
Natural gas	Methane (CH ₄) ~ 87%-96% Ethane (C ₂ H ₆) ~ 1.8%-5.1% Nitrogen (N) ~ 1.3 -5.6 Propane (C ₃ H ₈) ~ 0.1%-1.5% Carbon dioxide (CO ₂) ~ 0.1%-1% Traces of oxygen, isobutane, <i>n</i> -butane, isopentane, <i>n</i> -pentane, hexane and hydrogen	36.0 – 40.2
HFO	Carbon (C) – 85.1% Hydrogen (H ₂) – 10.9% Sulphur (S) – 4%	43 000

Table 3: Natural gas and HFO properties [66], [67]

2.3.2 By-product gas distribution and utilisation improvement models

Various procedures, techniques and mathematical models have been developed in an attempt to improve the utilisation of by-product gas on an iron and steel manufacturing facility. In this section, work that was done regarding the procedure, techniques and mathematical models are reviewed.

Studies like Hasanbeigi et al. [68] and Ouder et al. [69] review energy efficiency procedures and technologies to reduce CO₂ emissions and provide sustainable green steel manufacturing. These studies mainly focus on carbon emissions produced by the iron and steel industry and framework procedures to reduce it.

Porzio et al. [70], [71] developed a multi-objective optimisation evolutionary algorithms and compared it to a Linear Programming (LP) formulation using two different case studies. There is a need for multi-objective optimisation due to the requirement of reducing CO₂ emissions while maintaining economic sustainability.

One of the case studies was performed in nominal operating conditions and the other in off-design plant conditions. The results proved that CO₂ emissions could be reduced by more than 4% by using multi-objective optimisation. Additionally, the savings proved to be higher in operating conditions which the case study did not allow [70].

MILP models are some of the most often used optimisation models of by-product gas in the iron and steel industry. A MILP model is similar to an LP model but has the additional

capability to optimise with integers. The integers result in more complex optimisation algorithms which are more difficult to converge to an accurate solution [72].

The MILP optimisation models are used in the iron and steel manufacturing industry due to the on-site power generation plant. Boiler burners are assumed as a binary variable and thereby ensures that a burner can only be on or off [30]. An LP model cannot find a solution with the burners of the boiler either on or off but instead any rational number.

Akimoto et al. [73] were one of the first to propose a MILP approach for by-product gas supply distribution in the iron and steel industry at the Kawasaki Steel Mizushima works. The system was implemented on three platforms; a central computer, online process computer and digital instrumentation system. The software algorithm functioned according to three different steps which included the planning system, execution system and evaluation system.

The system calculated the optimal by-product gas supply to the on-site power generation plant. Operators were guided by the system. Automatic control was not used. The operators used the system to control reactively. The system was designed according to operation constraints specific to the plant [73].

MILP models have become increasingly complex and sophisticated from the work done by Akimote et al. [73]. Undesired operating conditions were minimised by assigning penalty functions introduced by Sinha et al. [74]. Different penalty function models were then developed and assessed by Valter et al. [30]. Kim et al. [75] improved the mathematical models representing the boilers.

Xiancong [32] proposed a MILP model considering Time Of Use (TOU) electricity tariffs. The model used Pareto optimality fuzzy sets to determine a solution with the contradicting objectives. Additionally, the model studied the relationship between the boilers' efficiencies and boilers' load. A case study was used to prove that the proposed model can be used to reduce electricity purchasing costs by up to 29.7%.

Sinha et al. [74] found that a MILP model can also be of benefit to other aspects of a steel plant such as the optimal distribution of oxygen, liquid iron break-even prices and quantities of purchased scrap. A MILP model was implemented on a Tata steel plant which optimally allocated resources for maximisation of profit.

2.3.3 Contributions of by-product gas utilisation and distribution models towards this study

Understanding the energy content of each by-product gas and substitute fuel gas can be used to focus the priority of by-product gas flaring reduction first with COG, followed by BOSG and then BFG. However, if significant volumes of BFG is available, it might be more sensible to prioritise according to energy volume produced.

Much work has been done on the optimal utilisation of by-product gas. The work has however, grown complex requiring many different and reliable inputs from the plant. South Africa's typical iron and steel producing plants do not have large varieties of accurate gas flow readings available. Energy and mass balances do typically balance making it dangerous to control accordingly.

2.4 Existing mathematical models for effective gas holder control

2.4.1 Gas holder's characteristics

The objective of this study includes the automatic control of a gas holder. Gas holders are expensive and dangerous components of an iron and steel producing facility. An overview of gas holders is required to ensure that the controller will operate the gas holder safely and efficiently.

Gas holders were originally designed for gas works where they served the same purpose as today. This purpose is to not only store gas but, also act as a regulator between a difference in production and consumption rates while providing the distribution pressure for the network [76].

Gas holders have always worked on the same principle as a vessel expanding and dropping. The mechanisms used for the expansion varies on the design type. The guides responsible for the movement differed alongside the development of the holders. Gas holders are either water-sealed or waterless [76]. Water-sealed gas holders are the more common of the two.

Gas holders on iron and steel manufacturing facilities contain by-product gas which is combustible. Containing a flammable gas is dangerous especially with a holder varying in volume. Bernatik and Libisova [77] conducted a study regarding loss prevention of large gas

holders. The study evaluates the risk of operation on six large gas holders. The study highlighted that almost all risks could be avoided by keeping a safe distance away for the gas holders.

The most important part of a gas holder control to this study is the operational constraints. Gas holders cannot utilise its full capacity. Figure 4 illustrates the operation parameters of a gas holder. Operation, preferably, needs to be done between the High (H) and Low (L) limits. The operation can however, also be done between High-High (HH) and high and also Low-Low (LL) and L. Operating beyond this level will potentially damage the gas holder.

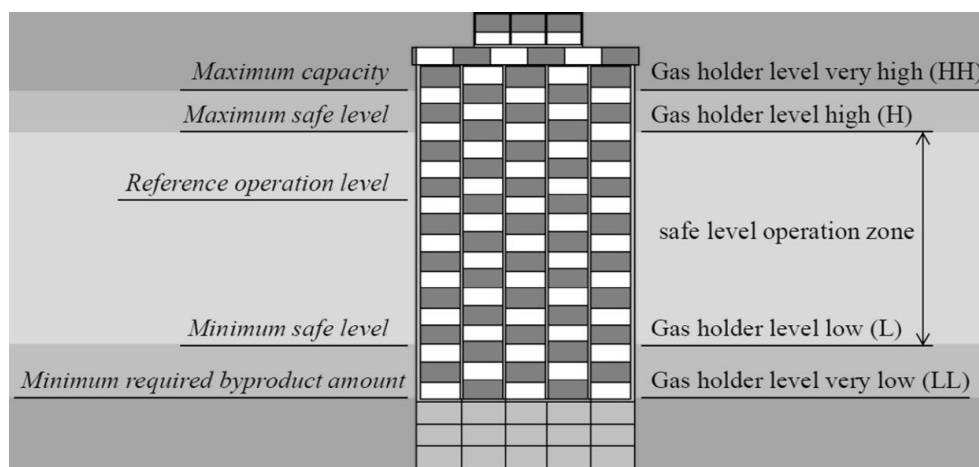


Figure 4: Gas holder operational parameters [30]

2.4.2 Gas holder mathematical models

Utilisation of gas holders have the ability to reduce flaring resulting in saving of money. This potential has led to research on optimal utilisation of gas holders. In this section, mathematical prediction and utilisation models developed regarding gas holders in the iron and steel industry are reviewed.

Su et al. [78], [79] investigated problems regarding the Hankel-norm output feedback and Takagi-Sugeno fuzzy system with stochastic disturbance. It was proven that it is practically impossible to establish a physics-based model to predict the level of a gas holder on an iron and steel facility.

Although a purely physics-based model cannot predict gas holder levels, various studies have proved successful when cumulative data from the plant is present. Zhao et al. [80] were able to accurately predict BFG using a two stage model based on an improved Echo State Network

(ESN). The first stage predicts the amount of BFG produced and consumed with a class of ESN and the second phase predicts the gas holder level by analysing the predicted level. The correlations are used to predict the gas holder levels.

Zhao et al. [81] were also able to successfully predict BFG using a multi-kernel algorithm. The study used a Multiple Kernel Learning (MKL) model that is based on Least Squares Support Vector Regression (LSSVR). The study proved that the model improved the prediction precision at a reduced processing rate compared to a traditional MKL due to the improved learning time.

Han et al. [82] proved that LSSVR could also be used to accurately predict by-product gas on a steel manufacturing facility. In the study, an improved least square support vector machine with a corresponding multi-output model was used. The study used experimental results based on real BOSG gas data to prove the effectiveness of the model on practical application.

Although the studies, [80]-[82] were successful in the prediction of by-product gas production consumption and gas holder levels, they are limited to short-term forecasts. Han et al. [83] achieved accurate long-term prediction results with a granular-computing based hybrid collaborative fuzzy clustering algorithm. The study was based on dated work completed on the long-term prediction of a time series [84].

Fuzzy stochastic optimisation models are an alternative that can be used to predict and control gas holders. Fuzzy logic differs from Boolean logic by functioning on more than the either true or false principle. Fuzzy logic includes any statement between true and false thus $0 - 1$. Therefore, the logic does include 0 and 1, but only in extreme cases. Computing according to increments between true and false resembles logic closer to the human brain [85].

Fuzzy logic is used in neural networks and artificial intelligence applications to develop human-like reasoning. Therefore, a fuzzy logic based artificial intelligent system can have the ability to function when faced with unfamiliar tasks [85]. A by-product gas distribution network has a vast amount of dependable factors which continually influence the gas holder's optimal decision making.

Su et al. [78] successfully constructed a full-order output feedback controller. The controller makes use of the Hankel-norm controller parameter transformation to overcome the Hankel-norm problem. Additionally, Su et al. [79] constructed a reduced-order model which can

translate the original approximation into a lower dimensional fuzzy switched system. Studies like the above mentioned, improve fuzzy based stochastic models which can in-turn be used on gas holders.

Wang et al. [86] developed a long-term prediction model to schedule BFG optimally. The study proposed a granular-based fuzzy model. A fuzzy inference model was constructed and used for the BFG scheduling rules. The system parameters and influential users are determined using a multi-layer coded generic algorithm. Validation of the study was done by implementing it on a case study proving accurate, safe and stable operation of the BFG system.

2.4.3 Contributions that work on gas holders have on this study

Control of a gas holder is relatively safe although it contains poisonous and combustible gas. The most important control parameter is that the holder remains between the high-high and low-low limits during operation. If control is beyond these limits, the gas holder can potentially be damaged.

A lot of work has been done on the prediction and scheduling of by-product gas using mathematical models which are based on gas holder utilisation. These projects delivered considerable savings. However, the models are complex, sensitive, intricate, and generally, requires a lot of inputs from the plant.

The South African iron and steel industry has a lack of skills and reliable data. Complex and sensitive models can be implemented if suitable data is available but maintenance of such a system will need to be done by a third party due to the lack of on-site skills. With the current state of CAPEX, the continual support of a third party make these types of solutions unattractive. A simplified and easily sustainable solution is thus required.

2.5 Energy expenditure tracking and measurement

The boundaries of this study include measurement of the controller benefit. Measuring the actual influence will allow for additional improvements. This section contains work that has been done on energy expenditure tracking and measurement. The by-product gas network is interlinked with a significant portion of the complete iron and steel producing facility, thus making it difficult to accurately quantify the controller benefit which is but a fraction of the system.

Demand Side Management (DSM) projects are cooperative projects with the objective to alter the customer electricity load profile. The load profile alterations are motivated by relieving demand for the electricity suppliers. DSM projects typically change the load profiles by peak clipping, valley filling, load shifting, strategic growth, strategic conservation, and flexible load shapes. Intrinsically, DSM projects are any measures that can be taken on the electricity load side to release any energy savings of the supply side [87].

The nature of DSM projects are similar to the project present in this study. It is due to the energy-saving focus of the project and that the project being implemented on the demand side which is equivalent to an iron and steel manufacturing facility. Additionally, the DSM programme was launched, in South Africa, by Eskom in 2004 [88]. Thus DSM projects have been active on South African facilities for more than 10 years. This makes DSM projects a good platform for this study.

Booyesen [89] developed several practical Measurement and Verification (M&V) methodologies, to improve the baseline model development process, applicable to industrial DSM projects. The study revealed that the field of M&V is well developed with good frameworks and guidelines. However, M&V on DSM projects have not been established as such.

The study used five DSM projects as case studies, and 31 different baseline models were developed. Each of the baseline models were variants of [89]:

- Constant baseline model;
- Energy neutral baseline model; and
- Regression baseline model.

A constant baseline model is the most basic model. The baseline consists of averages calculated for each operational model. The time over which the average taken is known as the baseline period. A constant baseline model is only applicable to systems with consistent operations. It is due to the averaged profiles of the models never being adjusted or compensated for systemic or operational changes [89].

An example of the ideal type of project of a constant baseline is a timer controlled lighting system. The timer would decrease the energy consumption of the lights consistently, therefore, easily measurable using a constant baseline. Cilliers [90] made use of constant baseline models

on a study involving mine dewatering pumps. The constant baseline proved sufficient due to the constant pumping cycles of the underground mines.

An energy neutral baseline is similar to a constant baseline but can measure fluctuating systems. This is due to the model adjusting according to the amount of energy consumed. An energy neutral baseline is developed in the same manner as the constant baseline. Therefore both constant and energy neutral models have the same profile. The energy neutral baseline does, however, adjust the amplitude of the profile according to the energy usage [89].

Energy neutral baselines are typically used on pumping and compressed air projects where load changes are periodically present [91]. An energy neutral baseline does not work well where there are general efficiency alternations being introduced [89]. An energy neutral baseline would reflect actual infrastructural improvements as the project's efficiency.

A regression baseline model is not limited to energy consumption as a means to accommodate systemic changes. With a regression model, any relevant independent variable of the system can be linked to the system power consumption. The most typical regression model used is a linear single variable regression model. There are however, more profiles that can be fit and multi-variable regression models for systems with more dependable factors [92], [89].

Booyesen [89] developed a baseline evaluation methodology which graphically presents the results using a histogram. Evaluating the performance of the baselines visually allow for an easy and clear distinction between different models. Graphical comparisons might prove to be useful in this study if more than one baseline is used.

2.6 Measures used to ensure project sustainability

The real success of an energy saving project is sustainability. It is of no use if the project was successfully executed and substantial energy savings were obtained for only a short period. Energy saving projects on systems continuously change and systems need to be maintained sustainably.

Groenewald [93] developed a new performance-centred maintenance strategy and proved its success by implementing it on ten different DSM projects. The new proposed maintenance strategy achieved an average electricity cost increase of 64.4% at an implementation cost of 6% of the benefit. The study based its proposed project maintenance strategy on the Plan to

Check Act (PDCA) cycle that was implemented by Javied et al. [94] who focused on the energy situation in the German industry.

Groenewald [93] realised that DSM projects tend to over perform during the Project Assessment (PA) phase but failed however, to achieve the sustained savings of the PA phase. The saving's reduction is possibly due to a lack of continuous attention to the DSM project after the PA phase.

Groenewald's [93] study identified the following reasons for failed sustainability:

- Failure of interference with the automatic control;
- Lack of suitable buffer capacity for load shifting projects;
- Plant and seasonal constraints preventing project saving targets;
- Facility overall condition; and
- Control philosophy problems.

The study presented the following maintenance types in Table 4 in attempt to reduce DSM projects' performance reduction after the PA phase. The project maintenance strategy presented in the study is dependent on how the controller was implemented and whether the plant implemented the controller itself. If the controller was not implemented by the plant itself, the contractual agreement between the implementation party and plant needs to be considered.

The importance of project maintenance can however, not be denied. Thus the maintenance strategy presented in Table 4 needs to be implemented after the controller has been commissioned.

Maintenance type	Description
Breakdown	Only performs maintenance on the project in the case that a breakdown occurs
Corrective	Improving or upgrading the facility's components and systems
Preventative	Performing suitable maintenance to ensure healthy performing equipment
Reliability-centred	Performing maintenance only on the components that have a direct influence on the reliability of the system
Productive	Focused on increased productivity with the minimum amount of maintenance

Table 4: Project maintenance types [93]

2.7 Conclusion

There is currently much work being done regarding energy efficiency in iron and steel manufacturing facilities resulting in sufficient BATs available to reduce energy significantly on steel producing facilities. The problem, however, is that the BATs require a high rate of change as well specialised knowledge and CAPEX. South African iron and steel producing facilities are unfortunately lacking in the latter two requirements.

By-product gas was identified as a suitable means to achieve energy savings. Several projects in recent work that was done revealed significant cost reductions achieved by optimising by-product gas control. The problem, however, is that the solutions require too many reliable inputs from the plant to be suitable for a typical South African iron and steel producing facility. Thus, a need exists for a simplified by-product gas controller.

Several energy measuring initiatives were identified consisting of a constant baseline model, energy neutral baseline model, and a regression baseline model. A broad understanding of baseline models is required for this study. The reason being that the project with the amount of potential noise as the controller's impact is hard to measure. Each of these baseline models or a combination of these models may be used.

Finally, the previous work done on project sustainability revealed that the single most important part for the sustainability of a project of this nature is the constant monitoring of the project performance. By monitoring the performance, adequate adjustments can be made when the controller is not delivering required results. If the controller is not updated with the system, the controller will not be used by the operators rendering the project of any energy savings.

Chapter 3 – Development of a simplified by-product gas controller



Figure 5: Steel plant active flare stack³

Methodology developed to design, simulate, implement and measure a sustainable by-product gas controller

³ Editorial Board, “U.S army corps receives judicious spanking over Cuyahoga river dredge shakedown: editorial”, [Online]. Available: www.cleveland.com/opinion/index.ssf/2015/05/us_army_corps_receives_judicio.html

3.1 Introduction

The overall objective of this study is to sustainably minimise the amount of by-product gas flared by improving and automating the gas holder, boiler and alternator's integrated control. Chapter 3 consists of the methodology developed to achieve this objective. The methodology was developed using a combination of the information gained from the literature review and experience for personnel working at the case study which is referred in to Chapter 4.

The methodology consists of three steps comprising of, (1) system evaluation, (2) design, simulation and implementation of by-product gas controller, and (3) procedure to evaluate the controller performance and provide sustainability. All three of these components are explained generically with the purpose to ensure a comprehensive generic solution to the study's objectives. Where applicable, examples are given to convey the concept correctly.

3.2 Overview of methodology

It is not possible to design a single controller which is suitable for all iron and steel manufacturing gas networks. This due to a significant amount of variations found in the iron and steel manufacturing industry. For example, steel plant distribution networks vary in size, gas holder type, alternator specifications, type of by-product gas reclaimed, etc. A generic methodology and controller was developed to allow for application on different networks.

A combination of the background, literature review and study objectives were the foundation on which the methodology is grounded. Figure 6 illustrates the methodology in chronological order using a flowchart. As depicted, from a holistic point of view, three stages were identified to complete the objectives of the study successfully. These steps include (1) system evaluation, (2) design and implementation of the controller, and (3) controller performance assessment.

A system evaluation needs to be done to identify the controller's design specification and amount of scope that the controller has. The assessment consists of three steps. First, the critical components required for the controller needs to be identified. Secondly, the system analysis to determine the amount of scope for the system. Finally, the system constraints are required, each component influenced by the controller needs to be individually investigated. When all the constraints are known and adhered to, the system will remain safe and compliant with operational capabilities.

Information for the system evaluation is used to design the controller in a compliant manner. The designed controller then needs to be simulated on a system representing the actual plant, to ensure that it is functioning as proposed. Once this simulation is approved, the controller needs to be implemented. Three different implementation strategies are proposed, and each of their pros and cons are discussed.

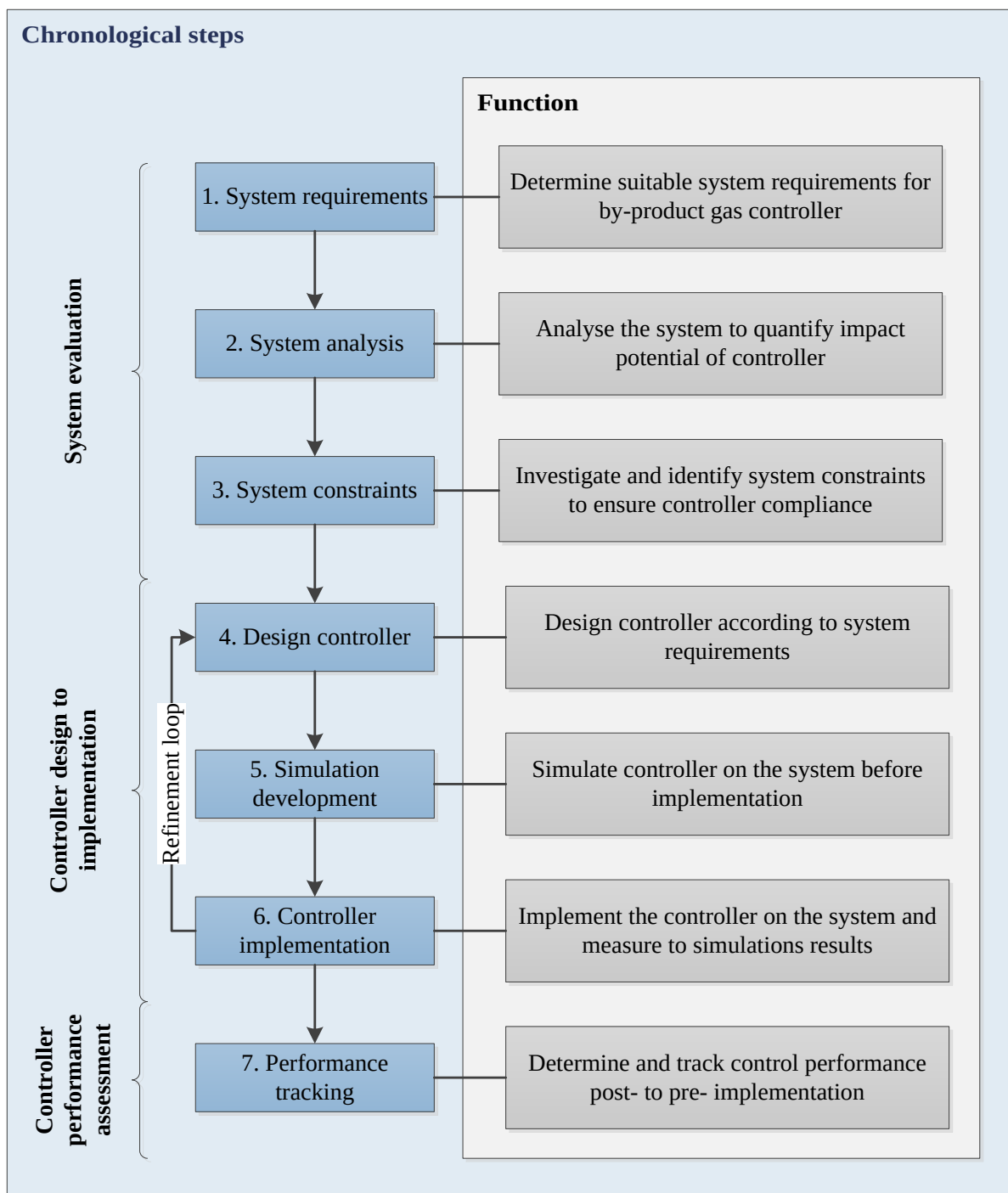


Figure 6: Overview of methodology for by-product controller

The project and so the methodology is concluded on the subject of performance assessment, tracking and project sustainability. Performance tracking is the key to success for the controller. This is due to the dynamic nature of the gas distribution network. Continuous changes on the system force periodic changes on the controller to remain not only functional but efficient. If tracking is not done, operators will stop using the controller as soon as the controller is not able to perform as desired.

3.3 System evaluation

3.3.1 Evaluation procedure

As previously mentioned, each iron and steel manufacturer differs from one another. The first step is to identify candidate plants, which are suitable and will be beneficial for a by-product gas controller. Identifying candidate plants consists of a set of prerequisite infrastructural requirements. Having only qualifying infrastructure does not make the system suitable.

The system needs to have the available capacity to benefit from a by-product gas controller. Therefore, a system analysis is required to calculate the possible impact of such a controller. With the necessary infrastructure and adequate amount of improvement scope, constraints on the operational and/or equipment can restrict, limit or disqualify the operation of a by-product gas controller. The required infrastructure, scope calculation and limitations are discussed in more detail in the following sections.

3.3.2 System requirements

The controller relies on improving the control between the amount of by-product gas flared and used to generate electricity by the plant itself. An on-site power generation plant is, therefore, one of the prerequisites for a suitable facility. As previously discussed, this study only focuses on the boiler – steam turbine power generation plant.

An interconnected distribution network is the next requirement. This distribution network is also where the gas holders and flare stacks are located as illustrated in Figure 2. The final and most apparent prerequisite is by-product gas recovery at the relevant plants. Figure 7 demonstrates that a by-product gas producer and gas recovery, by-product gas distribution network and an on-site cogeneration plant is required for the system to be suitable for the controller.

There will be no by-product gas to flare if the system does not have any plant producing, reclaiming and clean by-product gas. Thus either one or a combination of COG, BFG or BOFG needs to be generated, distributed across the facility, and used as fuel by the boilers to produce steam for electricity generation.

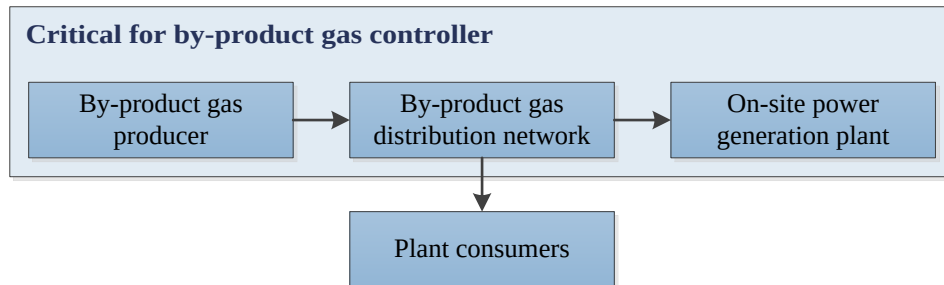


Figure 7: System infrastructural requirements for by-product gas controller

3.3.3 System analysis

Only after it has been identified, that the system has the required infrastructure, should a system analysis be done. A system analysis determines and evaluates the amount of scope available in the system for a controller. The potential energy savings should validate the time and resources spent in design and implementation of such a controller. It is of no use to implement a controller but not achieve a reasonable amount of energy savings.

The amount of scope is determined partially by the volume of gas flared, and partly by the capacity of the on-site power generation plant. If no gas is being flared, then no amount of flaring can be reduced. The same is in the case of the on-site power generation plant. If the system does not have any capacity left to generate electricity, then none of the by-product gas being flared can be spared.

The by-product gas network on an iron and steel manufacturing facility is unique to and integrated across the complete facility. The first part of the system analysis is to do a complete energy balance of the gas network for the facility. A mass rather than energy balance would also be suitable depending on what measurements are available at the facility. The balance of the facility gives a good overview of the weight each consumer carries.

The period of the balance must be of such that it removes the noise of the network without losing too much detail. The noise of the network is dependent on a number of consumers, and

the facility's overall condition. If the facility's condition has deteriorated to a point where there are constant stops and breakdowns, data would resultantly reflect these occurrences as noise.

It is important to note that the balances obtained by the facility are generally manipulated periodically. Typically, the data does not balance due to the lack of or inaccurate measurement readings. The data is balanced with experience from the plant typically on a weekly or monthly basis. These balances give a good enough overview of what weight each plant carries. However, it is not sufficient for a proper analysis of the potential savings for the controller.

The scope needs to be determined with the measured data itself. This would ensure that no possible mistakes were made on the facility's side in the data handling and/or balancing process. Therefore, using actual measuring data for scope analysis prevents the possibility of designing and implementing a controller that has no room to reduce the facility's energy costs.

The scope of the controller, therefore, lies in the amount of (1) by-product gas flared, (2) steam generated by boilers, and (3) electricity generated by boilers for a defined period. In this study, each of the calculations for the system analysis is normalised to GJ. Standardising the energy to GJ allows for the scope between the flaring, steam generation, and electricity generation compared against one another.

The total amount of energy saving potential is calculated using Equation 1. In this equation, it states that the minimum energy between the amount of by-product gas flared, additional steam generation capacity, and additional electricity generation capacity is equal to the energy saving potential.

$$\text{Energy saving scope}_{\Delta t} = \min(FS_{E,\Delta t}; BS_{E, \text{cap}_a, \Delta t}; AE_{E, \text{cap}_a, \Delta t}) \quad (1)$$

Where,

$$\begin{aligned} FS_{E,\Delta t} &= \text{By-product gas energy flared by plant for period } \Delta t \text{ [GJ]} \\ BS_{E, \text{cap}_a, \Delta t} &= \text{Boilers steam generation additional capacity for period } \Delta t \text{ [GJ]} \\ AE_{E, \text{cap}_a, \Delta t} &= \text{Alternators electricity generation additional capacity for period } \Delta t \text{ [GJ]} \end{aligned}$$

The total amount of by-product gas flared across the plant is calculated using Equation 2. The equation consists of the product of the flow of by-product gas to the flare stack and the by-product gas WI at a consistently selected period. Each of the different flare stacks and gases need to be added. An average of the WI is used rather than an instantaneous value due to the availability of accurate WI readings generally being low.

$$FS_{E,\Delta t} = \sum_{i=1}^{N_{FS}} \sum_F f_{i,t}^F WIF^F \Delta t \quad (2)$$

Where,

$f_{i,t}^F$ = Flow of gas F to flare stack i at time t [m^3/h]
 WIF^F = Wobbe index of gas F [GJ/m^3]
 F = BFG or COG
 i = Flare stack number; $1, 2, \dots, N_{FS}$
 N_{FS} = Number of flare stacks
 Δt = Period

Equation 3 calculates the additional steam producing capacity of the boilers. It is calculated as the difference between the maximum capacity that the boilers have and the actual amount of steam produced by the boilers for a predefined period.

$$BS_{E, cap_a, \Delta t} = BS_{E, cap_{max}, \Delta t} - BS_{E, cap_{utilised}, \Delta t} \quad (3)$$

Where,

$BS_{E, cap_{max}, \Delta t}$ = Boilers' maximum steam generation capacity for period Δt [GJ]
 $BS_{E, cap_{utilised}, \Delta t}$ = Boilers' steam generation capacity utilised for period Δt [GJ]

The boilers' steam production capacity and actual production are calculated using Equations 4 and 5. Both equations are functions of the boilers' efficiency. It is import to ensure the real boiler efficiencies are used and not just use the data sheets indicating the design specifications. The reason being that the boilers may have been modified or deteriorated over the years. Ideally, actual flow data should be used to verify boilers' efficiency.

$$BS_{E, cap_{tot}, \Delta t} = \sum_{j=1}^{N_B} BS_{S, cap_{max}, j, t} \eta_{B_j} \Delta t \quad (4)$$

$$BS_{E, cap_{utilised}, \Delta t} = \sum_{j=1}^{N_B} BS_{S, cap_{utilised}, j, t} \eta_{B_j} \Delta t \quad (5)$$

Where,

$BS_{S, cap_{max}, j, t}$ = Maximum steam generation capacity for boiler j at time t [tonne steam/h]
 $BS_{S, cap_{utilised}, j, t}$ = Utilised steam generation capacity for boiler j at time t [tonne steam/h]
 η_B = Boilers combined efficiency [$GJ/tonne\ steam$]
 j = Boiler number; $1, 2, \dots, N_B$
 N_B = Number of boilers
 Δt = Period

Similar to the boilers, the additional alternator capacity is calculated by subtracting the amount of electricity actually being generated by the electricity generation capabilities. Equation 6 should be used to determine the total amount of additional electricity generation of the alternators.

$$AE_{E, cap_a, \Delta t} = AE_{E, cap_{max}, \Delta t} - AE_{E, cap_{utilised}, \Delta t} \quad (6)$$

Where

$AE_{E, cap_{max}, \Delta t}$ = Alternators' maximum electricity generation capacity for period Δt [GJ]
 $AE_{E, cap_{utilised}, \Delta t}$ = Alternators' electricity generation capacity utilised for period Δt [GJ]

Equation 7 and 8 calculates the total alternator capacity and the alternator production. Both equations are functions of the alternator efficiency, similar to the boiler calculations.

$$AE_{E, cap_{max}, \Delta t} = \sum_{k=1}^{N_A} AE_{G, cap_{max_{k,t}}, \Delta t} \eta_{A_k} \Delta t \quad (7)$$

$$AE_{E, cap_{utilised}, \Delta t} = \sum_{k=1}^{N_A} AE_{G, cap_{utilised_{k,t}}, \Delta t} \eta_{A_k} \Delta t \quad (8)$$

Where

$AE_{G, cap_{max_{k,t}}}$ = Maximum electricity generation capacity for alternator k at time t [MW]
 $AE_{G, cap_{utilised_{k,t}}}$ = Utilised electricity generation capacity for alternator k at time t [MW]
 η_{A_k} = Alternators combined efficiency [tonne steam/MWh]
 k = Alternator number; 1, 2, ..., N_A
 N_A = Number of alternators
 Δt = Period

Additionally, trends can be drawn using consecutive time periods as a means to predict what the energy saving scope would be in the future. It is typical for larger iron and steel producers to fluctuate in production periodically due to large shutdowns, alterations, improvements, and demand. However, with proper curve fitting and correspondence within the plant, accurate predictions can be cast.

3.3.4 System constraints

The final part of elevating a system before proceeding with controller design is the system constraints. Identification of the system constraints serves two functions. The first, ensuring

that the equipment has the ability to accommodate a by-product gas controller, and the second, providing the controller's design specification for the parameters of the controller.

It is of utmost importance that all the operational constraints are investigated and studied. Without a proper understanding of these constraints, it is possible for the controller to be either unsafe or pose a risk to the equipment which is involved in the process. The limitations of each of the following sections are discussed; by-product gas, distribution network, gas holder, boilers and the alternators.

By-product gas – The only constraint regarding by-product gas is the production rate and quality of the by-product gas produced at the coke ovens, blast furnace and BOF. If the by-product gas is not cleaned sufficiently, the distribution network will get clogged up and burns stuck. Additionally, it will also make the boilers of the on-site power generation plant unstable if the calorific value (CV) fluctuates too much.

Distribution network – Considering the distribution network, the constraints are with the control used and metering equipment. The accuracy of metering readings is generally a problem regarding by-product gas networks. The reason for this is a significant number of impurities found in the gases. Metering data must be reliable at all costs to be used for the controller. This is of utmost importance as false readings are a risk for automatic control.

Gas holder – Gas holders typically have water seals. The only constraints the gas holders have on the controller are operation levels. Most gas holders are operated by four different levels. These levels include high-high, high, low and low-low. The holder's level is not allowed to rise above high-high or below low-low.

Operation between low-low, low and high-high, high should be avoided but is regarded as acceptable. Should the gas holder level drop below low-low then the gas holder might get damaged. However, operation above the high-high level is restricted as the high-high is generally the set point to flare any excess gas. Gas holder operation is therefore a constraint between the high-high and low-low levels.

Flare stack – A flare stack is constrained by a maximum gas flow. The flare rate of by-product gas is typically not a restricting parameter.

Boilers – Boilers are constrained by the type of burners used and the rate of change in the steam generation. There are different types of burners each with their pros and cons. It is important to consider the burners used at the boilers and their adjustment constraints. Additionally, boilers can become unstable if the rate of steam generation is changed too drastically.

Alternators – Similar to boilers, alternators are constrained by the rate of change of electricity generation. The design parameters of the alternators need to be considered. Typically, a velocity control needs to be implemented on the electricity ramp up and down rates to ensure safe alternator operation.

3.4 Controller design to implementation

3.4.1 Controller design

The information gained during the system evaluation is used as the design parameters for the controller. Intrinsically, the by-product gas controller actively controls the amount electricity generated according to the by-product gas volumes. Active control is achieved by automating the decision between flaring, storing or generating steam with the by-product gas.

This type of control should, however, be done with the minimum amount of inputs due to unreliable flow data from the plant side. To understand the solution, the control interaction between boilers and alternators needs to be understood. Boilers' steam generation typically works with a cascade control system controlling consumption of fuel to meet the header steam pressure set point.

The amount of steam consumed by the plants is automatically replaced with the boilers maintaining the header pressure. For example, any plant consuming more steam would result in the pressure of the steam line dropping. Therefore, the header pressure of the boilers would drop as well, and the control system would automatically increase the fuel gas consumed by the boilers in order to maintain the set header pressure.

This principle is similar for the alternators. If the electricity generation set point for the alternators is increased, more steam would be consumed resulting in the boilers automatically adjusting the amount of fuel gas consumed to generate the required header pressure to sustain the system. Therefore, the amount of by-product gas consumed by the boilers can be controlled by the electricity generation of the alternators.

The control interaction between the alternators and boilers is illustrated in Figure 8. If the set point of the alternator's electricity generation adjusts, so does the steam control valve and by-product gas or HFO consumed by the boilers.

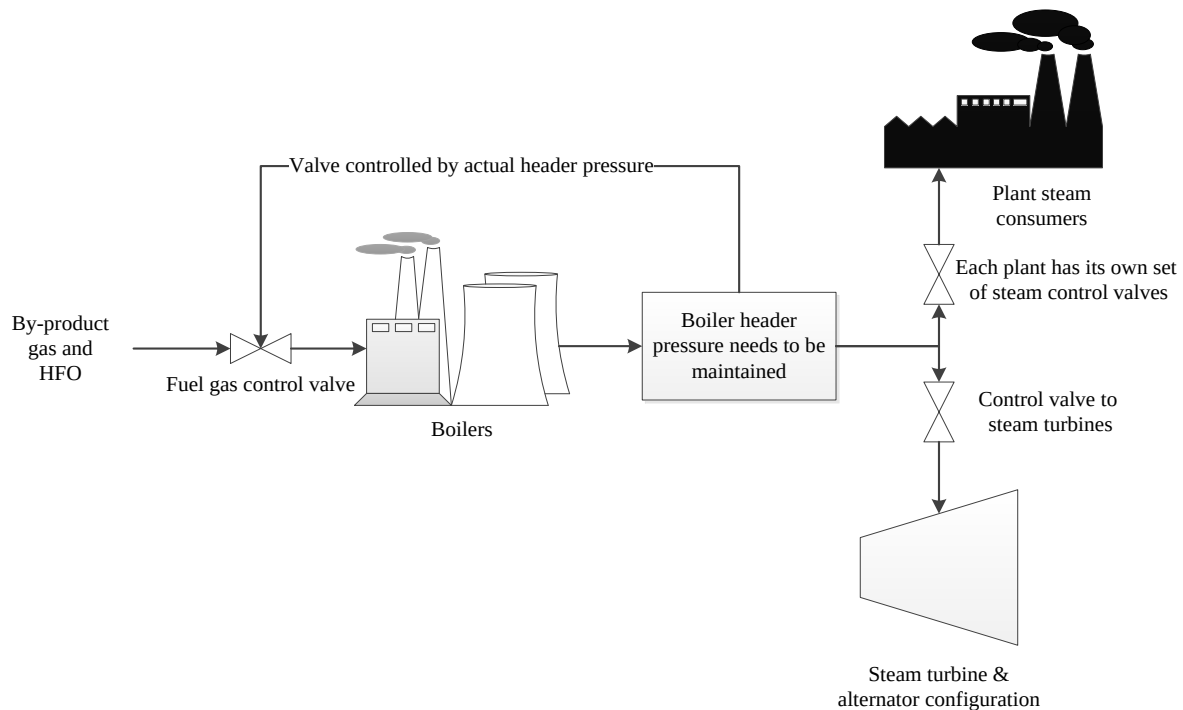


Figure 8: Boiler and alternator integrated control network

The controller controls the amount of by-product gas sent to the boilers by adjusting the electricity generation of the alternators. The gas holder's level is the best indication of the condition of the by-product gas network. If too much gas is produced for the consumers, the gas holder level will automatically increase. The same is true if too little gas is being produced, the gas holder level will decrease.

The control functions by analysing the level of the gas holders and adjusting the alternators' electricity generation set point accordingly. If the gas holder is relatively high, the generation set point should be high, and if the holder level is relatively low, the electricity generation set point should be low. This type of control will constantly attempt to stabilise the by-product gas holders, therefore, resultantly reducing by-product gas flaring.

If the by-product gas network is controlled in the above proposed manner, then the electricity generation would also be proportional to the amount of by-product gas available in the system. This concept is illustrated in Figure 9 where the available surplus by-product gas volumes in the system is proportional to the electricity generation.

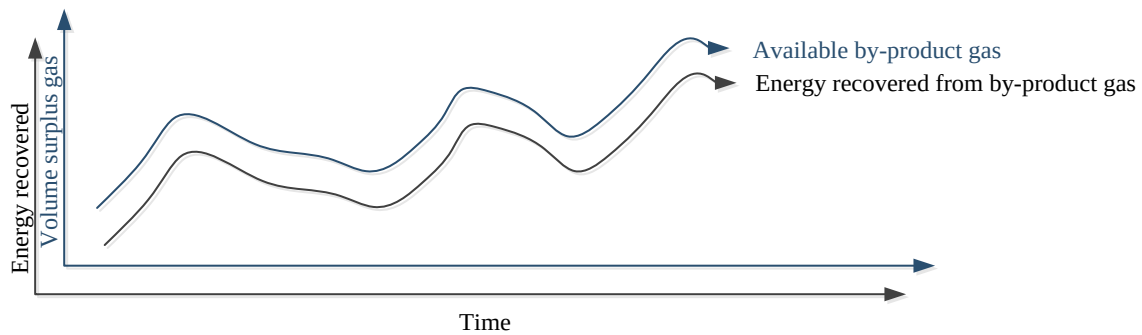


Figure 9: Illustration of controller by-product gas utilisation

Figure 10 illustrates the effect that the controller will have on the by-product gas network with a SANKEY diagram. The combined stream of by-product gas sent to the boilers and flared remains around the same region. However, the controller increases the ratio of by-product gas sent to boilers compared to flare. Thus for the same amount of by-product gas available, a more significant portion of this gas will be used to produce steam for electricity generation.

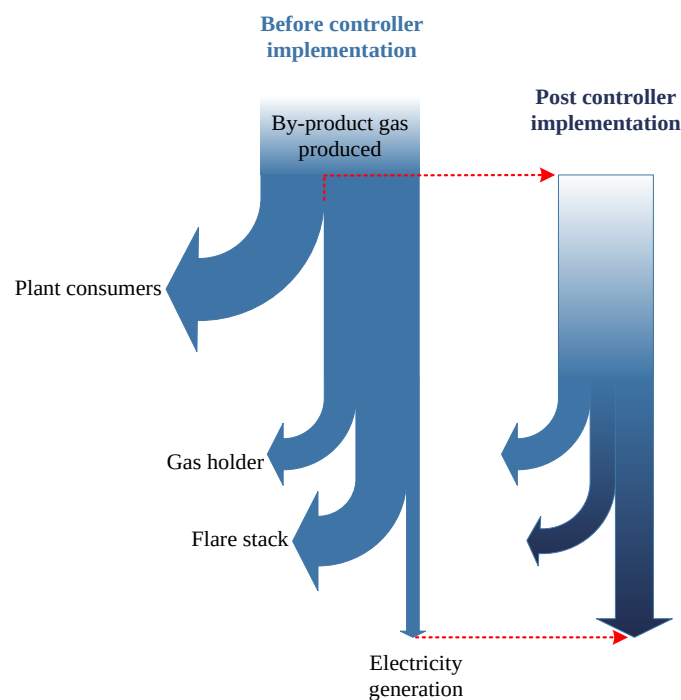


Figure 10: Influence of controller illustrated by SANKEY flow diagrams

Controlling the alternator set point according to the gas holder level can be done in two ways. The first being a tier type of control. A tier type of control selects a constant electricity generation set point according to a gas holder level band. The second type of type of control is continuous. A continuous type of control determines the electricity generation set point, instantaneously, according to a curve formula which is a function of the gas holder level.

Figure 11 and Figure 12 are examples of control based on tier and continuous type of control. The distinct discrepancy between the two methods lies in the electricity generation steps found with the tier type and not with the continuous type of control.

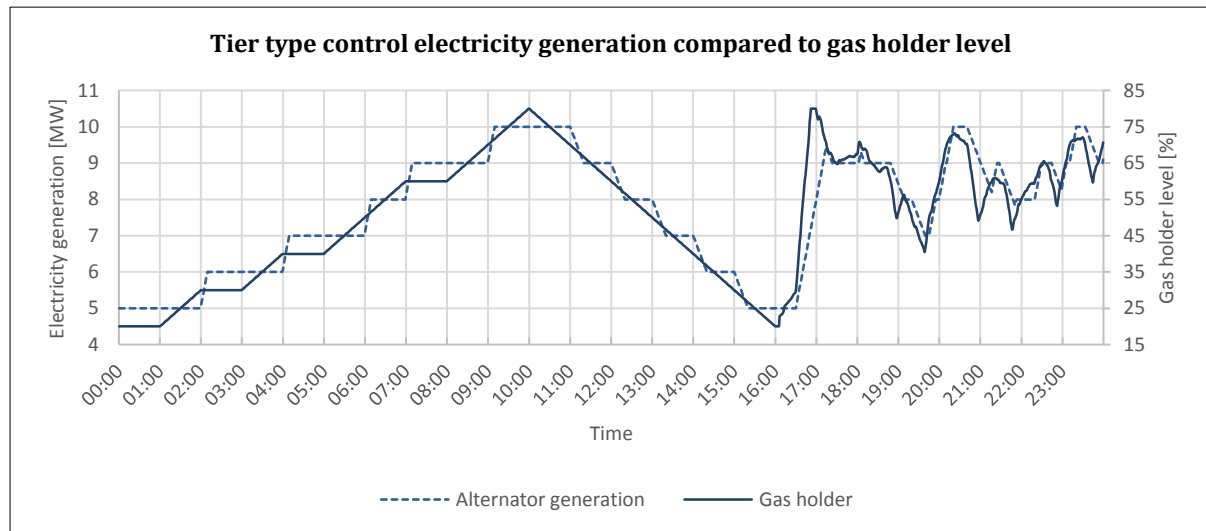


Figure 11: Example of a tier type by-product gas controller

As for the continuous control, the alternators and boilers need to be able to accommodate the continuously changing set points. Construction of a tier controller is specific to each plant. The amount of tiers, electricity generation, limits and ramp up and down rates are all determined by facilities parameters. With the tier design, the operation region can also be manipulated according to the designer's desires.

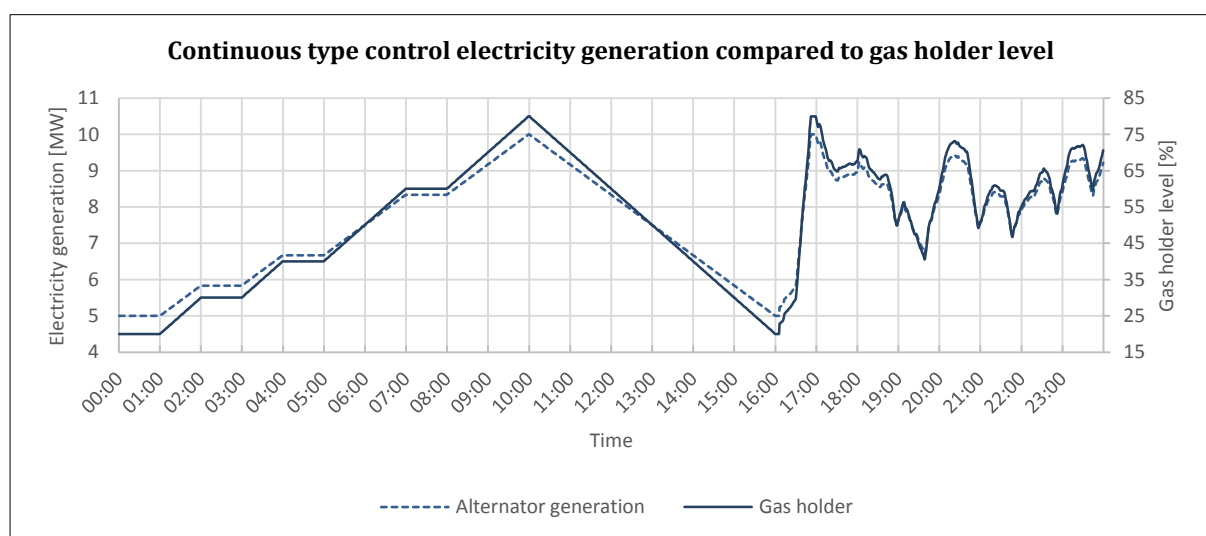


Figure 12: Example of a continuous type by-product gas controller

The tier type controller will typically be designed using logical operators. For example, if the gas holder level is greater than 50% and smaller or equal to 60%, then the electricity generation should be 5 MW. With the continuous type of control, a single equation is used to instantaneously determine the electricity generation.

Equation 9 was developed to determine a continuous electricity generation set point according to the generation and gas holder limits. Thus, the equation determines an electricity generation set point continuously with the objective intent to stabilise the gas holder level. It is important to note that Equation 9 serves only as a foundation to continuous gas holder control and can be modified to satisfy the plant's conditions.

$$ALT_{SP} = \left[(AE_{G,max} - AE_{G,min}) * \frac{GHL_{actual} - GHL_{LL}}{GHL_{HH} - GHL_{LL}} \right] + AE_{G,min} \quad (9)$$

Where,

ALT_{SP}	= Alternator set point [MW]
$AE_{G,max}$	= Alternator maximum generation limit [MW]
$AE_{G,min}$	= Alternator minimum generation limit [MW]
GHL_{actual}	= Actual instantaneous gas holder level [%]
GHL_{LL}	= Low-low gas holder level [%]
GHL_{HH}	= High-high gas holder level [%]

The design of each controller is going to be different. This section should only serve as a foundation on which the controller is based. Thus the developed controller will be a variant of either a tier or continuous based controller. It is not possible to design a single controller able to function optimally on all by-product gas distribution networks.

3.4.2 Simulation development

A simulation needs to be developed to simulate how the controller will perform on the actual system before implementation. The simulation must be able to simulate the interaction between the surplus by-product gases, the gas holder, flare stack, steam and electricity generation. It is important that the actual characteristics of the facility's network is used for the simulation.

The simulation needs to consist of the following sections:

- Actual plant inputs;
- System constraints;
- By-product gas controller; and
- Gas and energy balancing logic.

Actual plant constants and efficiencies, as well as constraints, are required to resemble the true system. All of these parameters and constants need to be accurate and if not, a false confidence might be misaligned and possibly dangerous. Parameters and constraints include alternator limits, gas holder limits, COG WI, BFG WI, BOSG WI, boilers' efficiency, alternators' efficiency, gas holder volume, etc.

In order to understand the plant and the consumers, a mass balance must be done to the consumers on the gas networks for the facility. The mass balance must be completed first because all of the flow meters will typically be reading a volume flow rate. From the mass balance, an energy balance must be derived. The energy balance is there to give a better indication of where most of the energy is being sent. This will give different perspectives due to each gas having a different WI.

The mass and energy balance will also determine the accuracy of the plant's instrumentation. A defective flow meter or gas analyser will be picked up in the process. It is important to determine whether the plant has adequate equipment because the controller is going to be used automatically and it is going to function based on the plant's readings. If the readings are inaccurate, then the controller has the risk of putting people's lives at risk or having the risk of damaging equipment.

The simulation must be built based on the current control philosophy of the plant. If the current control is manual, then an elemental controller must be designed initially. The simulation development can only proceed once the plant is deemed as suitable by considering the infrastructure, scope and constraints.

3.4.3 Controller implementation

After the controller has been simulated and approved by the plant, it needs to be implemented. Three different options are available to implement the controller depending on the plant and type of control used. The first of the options, being the ideal scenario, is where the controller can be implemented into the SCADA system.

The second implementation method is to use a live program and give access to a graphical user interface (GUI) on a computer to the operator. Alternatively, the controller can be implemented as an instructional guide. Figure 13 illustrates the different implementation methods for the implementation of the controller.

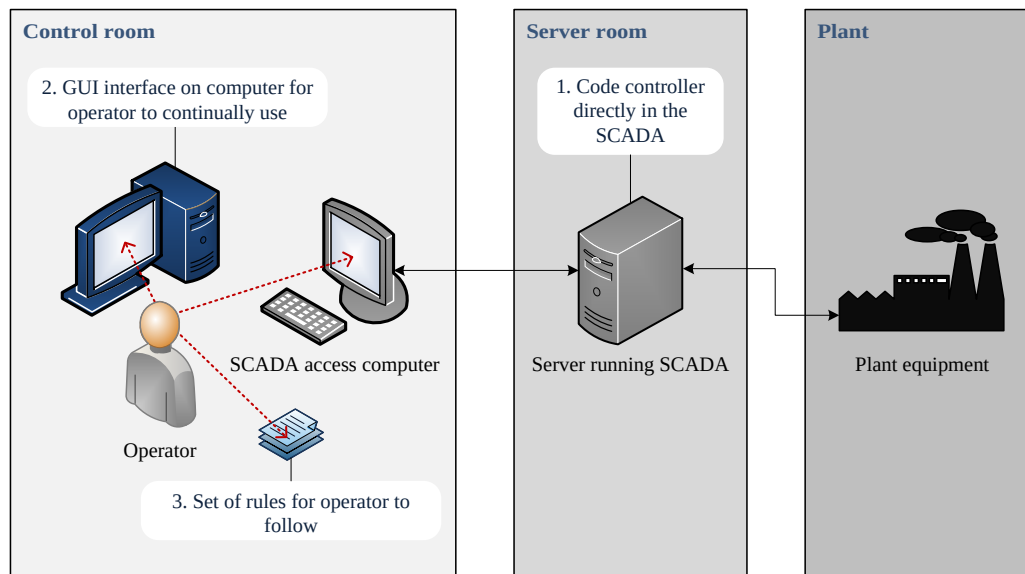


Figure 13: Schematic of by-product gas controller implementation possibilities

Implementing the control directly into the SCADA results in the control being active. Whereas using a different computer to view to optimal control or following a set of rules are reactive. Thus option 2 and 3 gives the operator instructions to control accordingly.

Active control has got two distinct advantages. The first advantage of active control is continuous and consistent control. Thus there are no instances that the controller can forget about adjusting the generation whereas an operator can get distracted. The second advantage is that the control is consistent. An operator has the ability to make mistakes.

Implementing the control into the SCADA relieves the workload from the operator. It is crucial for the SCADA system to have enough safety precautions to remove the operator and still have a safe system. In the case of using two different computers, the controller needs to be developed into a program.

The program must have an appropriate GUI and the ability to communicate with the live data. It is important that the GUI's functionality is clear and easy understandable to the operators. If the GUI is complicated, the risk is that the operators would not use it, exists. The live data would typically be connected using an OLE for Process Control (OPC) server.

Using the controller as a set of rules for the operators is the last option. The reason is that the operators already have many different systems to control. It would be difficult for them to focus on the all the operations and successfully implement the controller according to the rules supplied. Operators may also put their twist on the controller without understanding the rules.

3.5 Procedure to evaluate controller performance

3.5.1 Controller measurement overview

After the controller has been successfully implemented, the project performance must be measured. Thus, the controller is validated by providing a suitable monetary saving for the facility. For the controller to be measured, a baseline model needs to be developed. Due to the complexity of the gas network, several possible baseline models were developed in this study.

Each model has its own set of advantages and disadvantages. It is important to realise that none of the models will be completely accurate due to a large amount of influencing factors. Under the ideal circumstance, a clear reduction in the flaring of the by-product gases will be reflected in the actual plant data. Thus, comparing pre-controller implementation to post-controller implementation data will show a reduction in the amount of by-product gas flared.

The measurement difficulty lies with the noise in the gas data that typically hides the impact of the controller. Noise results from the pseudo-random behaviour plant that consumes by-product gas and unexpected breakdowns and shutdowns. An additional four baseline models are proposed in this study.

The objective of a baseline model is to provide a measurement procedure to quantify the impact of an initiative. A baseline model consists of the baseline boundaries, baseline period, metering tags, routine adjustments, saving quantification, and non-routine adjustment. The baseline model boundaries isolate the baseline and impact of the controller. If the boundaries are wrongly defined, the controller will affect the plant at a downstream section unknowingly.

3.5.2 Boundaries of the baseline model

The boundaries of the baseline should only include the mechanisms involved with the controller. The controller determines the electricity generation based on the gas holder level. Thus, the boilers generating the steam, alternators generating the electricity, the gas holder used for the decision making and flaring the parameter being reduced should be included in the baseline boundary. Figure 14 illustrates the sections which are included and excluded from the baseline boundary.

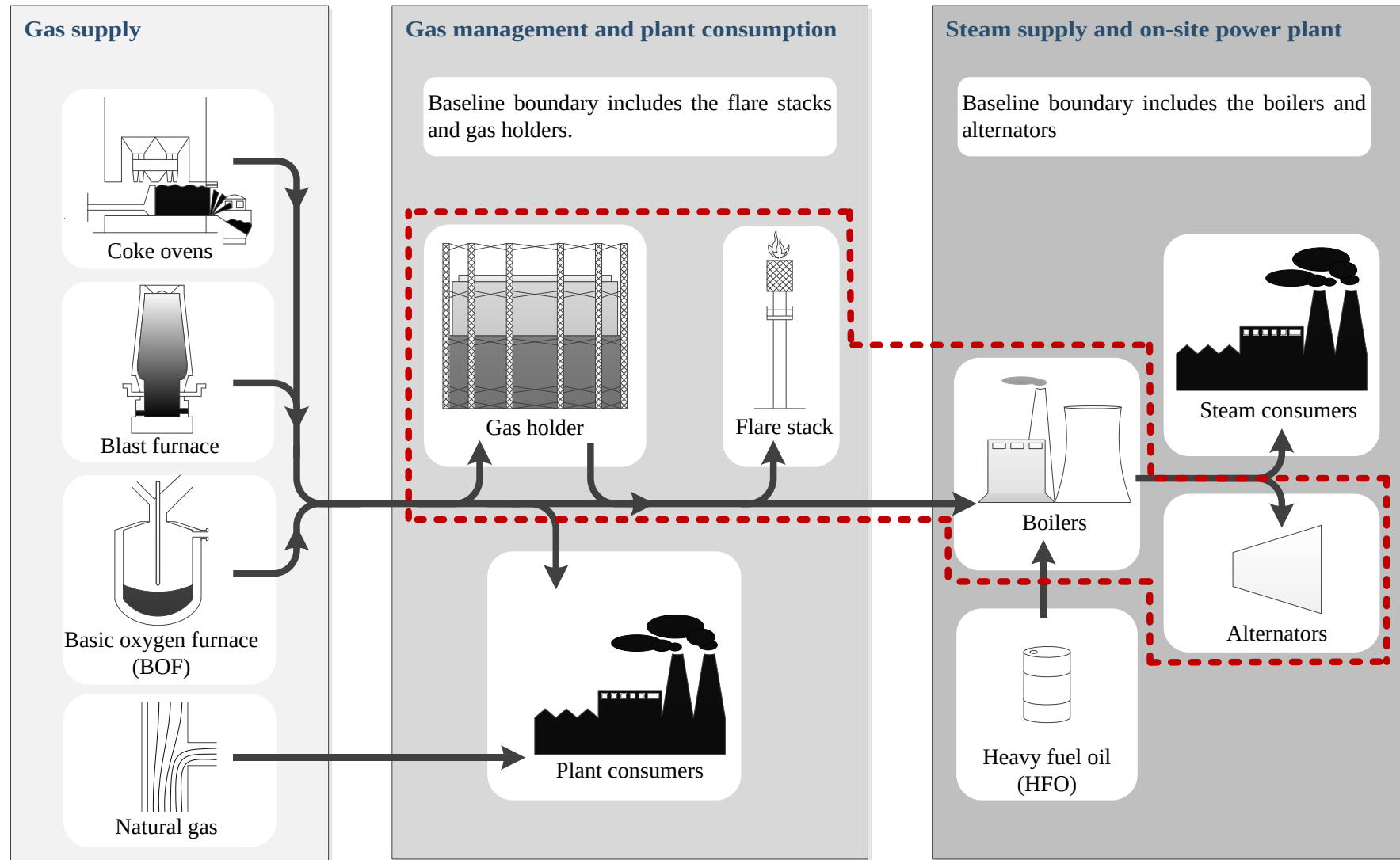


Figure 14: By-product gas distribution network baseline boundaries

3.5.3 Baseline period

A typical by-product gas distribution network is interlinked with the complete facility. A significant amount of plants and infrastructure involved results in much noise in the measurements, as well as the system changing constantly. Noise can be caused by anything from production fluctuations to short-term breakdowns. The system's characteristics can vary due to the large-scale shutdowns and infrastructural improvements.

Both these difficulties need to be addressed with the baseline period. Using the data closest to the implementation ensures that the system characteristics are as constant as possible. Measurements from too far in the past could possibly not reflect the actual system conditions than when the controller has been implemented. The period directly before implementation does, therefore, address the varying system characteristics but not the noise.

The noise needs to be minimised using an average of a suitable period. An average over a period balances out the noise due to constant fluctuation in the systems. Therefore, it is suggested that a month's data before the controller implementation should be used.

3.5.4 Metering and data tags

The metering tags for both the baseline period and performance assessment need to be raw data. Thus unprocessed data from the flow meters itself. Unprocessed metering data avoids the risk of unreliable or outdated compensations and alterations made to data.

3.5.5 Routine adjustments

Baseline model 1

In the ideal case, a clear reduction in by-product gas flared can be seen after the controller has been implemented. The gas distribution network, by-product gas production and consumption, needs to be relatively constant for such a clear by-product gas flaring reduction. For such an instance, a constant baseline model needs to be used for performance measurement (see Section 2.5).

In Figure 15, an example of a how a constant gas distribution network would perform before and after the controller implementation is displayed. On the graph, the daily amount of

by-product gas is plotted in GJ. The data consists of 62 days, where the first 31 days are before controller implementation and the second 31 days after the controller was implemented.

The data show signs of noise around day 21 to day 24 and around day 51 to 54. The noise is not enough to hide the apparent differences of before and after implementation. This is seen in the averages illustrated in Figure 15. The average before implementation is just above 2000 GJ by-product gas flared and the average after is slightly above 1500 GJ by-product gas flared. Therefore, the flaring of by-product gas has been reduced by the controller with 500 GJ.

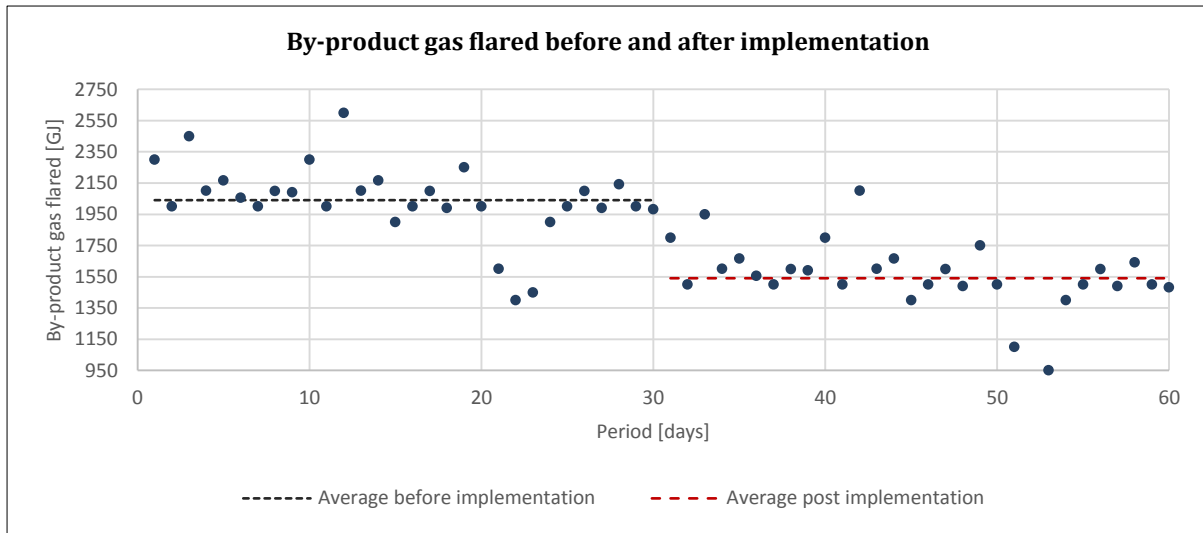


Figure 15: Example of a consistent network before and after controller implementation

Even though the by-product gas benefit can be seen clearly in data that is represented in Figure 15, the routine adjustment needs to be defined. The routine adjustment would be the average of the by-product gas flared daily GJ over the baseline period (Equation 10). This routine adjustment will not change unless a non-routine adjustment needs to occur.

$$BM_{RA} = avg_{BP}(FS_{E,\Delta t}) \quad (10)$$

Where,

- BM_{RA} = Baseline model routine adjustment [GJ]
- $FS_{E,\Delta t}$ = By-product gas energy flared by plant for period Δt [GJ]
- Δt = Period
- avg_{BP} = Average for baseline period

Figure 16 illustrates an example of the data from Figure 15 presented in a performance tracking format. The red line is the routine adjustment and the blue markers the data post-controller implementation. The model is however, completely dependent on a consistent and reliable gas network and consumer demand. In the case that the gas distribution network would slightly change or a consumer is down, the amount of by-product gas available would change and be noise in the network.

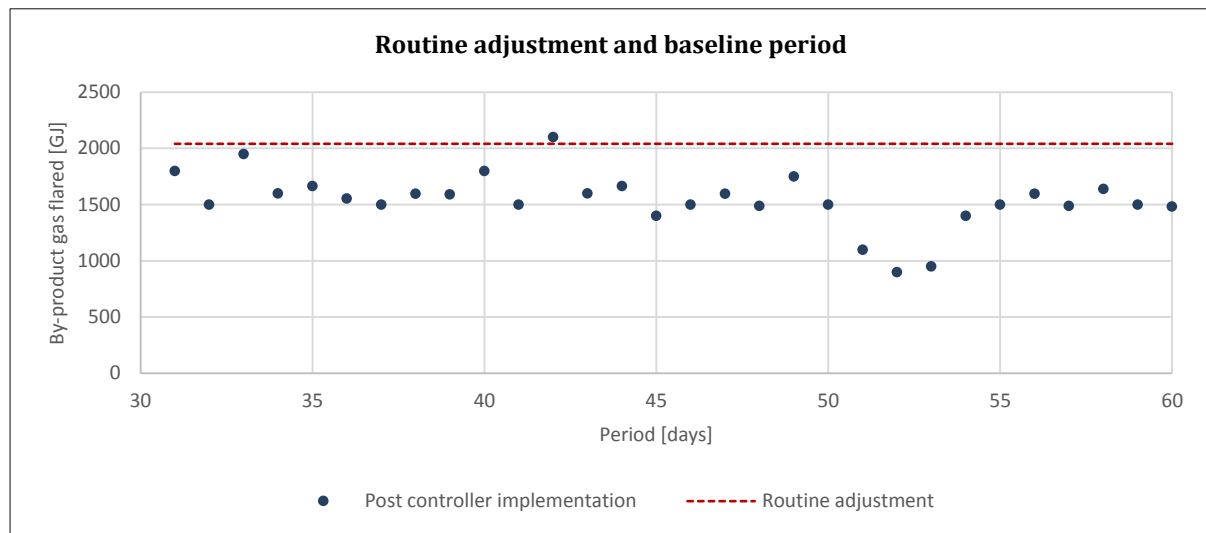


Figure 16: Example of Baseline model 1 routine adjustment and flaring

Gas distribution network on a steel plant, unfortunately, typically contains too much noise for a constant baseline. Baseline model 2 to 5 addresses the system noise - each by a different approach.

Baseline model 2

Baseline model 2 eliminates the influence of system noise by using a constant flaring reduction percentage. A constant by-product gas flare reduction is calculated through simulation. The routine adjustment factor for the project will be determined by comparing the simulated flaring using automated control with flaring during the baseline period.

An example of a gas distribution network with too much noise for a constant baseline is illustrated in Figure 17. Similar to Figure 15, the data is of the daily amount of by-product gas flared in GJ of data pre- and post-controller implementation. The first 31 days before controller implementation and the days after post-controller implementation.

The data resembles a large cloud with no pattern or difference between the data of before and after implementation. Both the averages of the by-product gas flared pre- and post-implementation is slight above 1000 GJ.

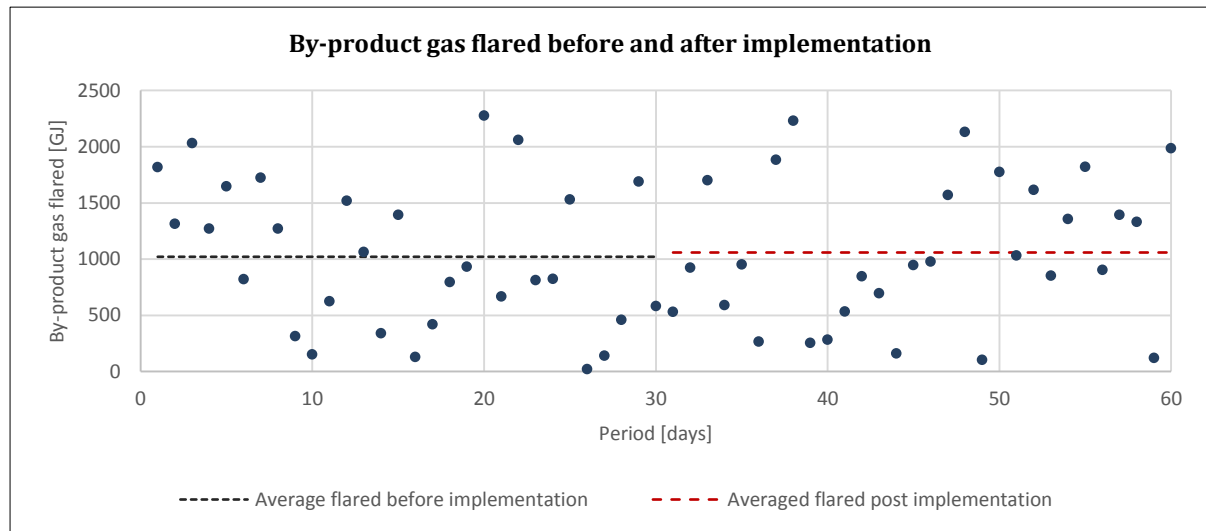


Figure 17: Example of an inconsistent gas distribution network before and after controller implementation

The percentage difference between the simulated and actual flaring will then be used to calculate flaring reduction after project implementation. Figure 18 illustrated the concept; the red data points are the same data as the blue but simulated how the controller would influence the system. The flaring reduction is calculated by the difference in the amount flared by the blue and red data point for each day.

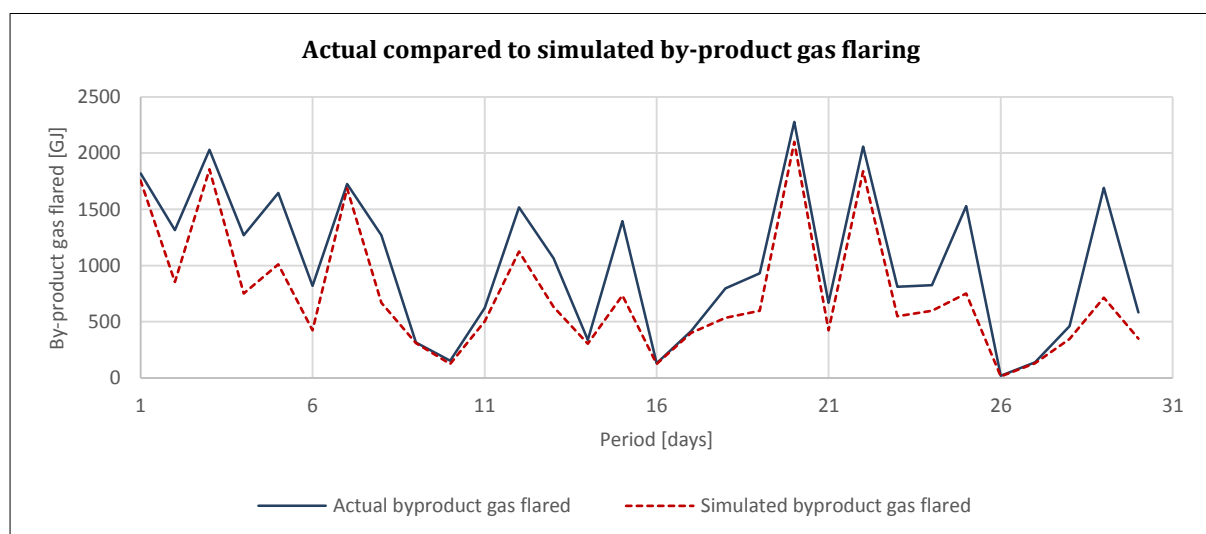


Figure 18: Example actual compared to simulated control by-product gas flaring

The flaring reduction of each day differs, this is due to the system having many dependants. Therefore an average of the flaring reduction percentage over the baseline period needs to be used. It is import to realise that this model will have a large variation between the simulated flaring reductions due a combination of the system being operated manually by humans and the amount of plants that have an influence. The flaring reduction factor is calculated using Equation 11.

$$FS_{reduction} = \frac{avg_{BP}(FS_{E,\Delta t}) - avg_{BP}(FS_{Esim,\Delta t})}{avg_{BP}(FS_{E,\Delta t})} \quad (11)$$

Where,

$FS_{reduction}$	= By-product gas flaring reduction factor [%]
$FS_{E,\Delta t}$	= By-product gas energy flared for period Δt [GJ]
$FS_{Esim,\Delta t}$	= Control active simulated byproduct gas energy flared for period Δt [GJ]
Δt	= Period
avg_{BP}	= Average for baseline period

The routine adjustment constant would, therefore, be a fraction of the actual amount of by-product gas flared. An example of this is presented in the data from Figure 18. A flaring reduction factor was calculated as 26%. Therefore, the routine adjustment will be calculated as the actual flaring with the additional 26%. Equation 12 is used to determine the routine adjustment.

$$BM_{RA} = FS_{E,\Delta t} * \left(\frac{100}{100 - FS_{reduction}} \right) \quad (12)$$

Where

BM_{RA}	= Baseline model routine adjustment [GJ]
$FS_{E,\Delta t}$	= By-product gas energy flared by plant for period Δt [GJ]
$FS_{reduction}$	= By-product gas flaring reduction factor [%]

For example, 2000 GJ of by-product gas is flared after the controller has been implemented and the baseline model has a flaring reduction factor of 26%. The 2000 GJ flared would have been 26% more if the controller was commissioned. Thus, the routine adjustment is the 2000 GJ with the addition 26% as calculated in Equation 13 and 14.

$$BM_{RA} = (2000) * \left(\frac{100}{100 - 26} \right) \quad (13)$$

$$BM_{RA} = 2703 \text{ GJ} \quad (14)$$

Therefore, the benefit that the control had is the 703 GJ. Baseline model 2 differs from model 1 due to the routine adjustment being proportional to the actual flaring volume. This concept is illustrated in Figure 19, where the same data set from Figure 17 is used. The routine adjusted values are calculated on the data post-controller implementation. A flaring reduction factor of 23% was used.

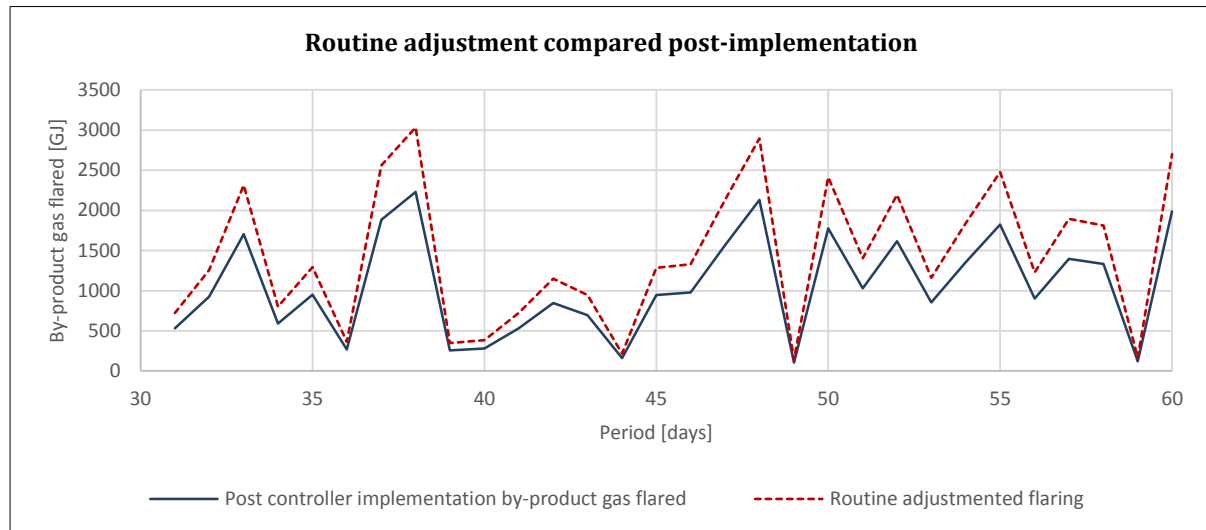


Figure 19: Example of Baseline model 2 routine adjustment and flaring

Baseline model 2 has the advantage to proportionally adjust according to the amount of gas available. This is an advantage compared to model 1 where a constant average is used. However, the model does not consider electricity generation at the alternators. Baseline model 3 incorporates the alternators within the baseline model.

The disadvantage of Baseline model 2 is that if maximum generation is reached and there is too much gas available, then a significant amount of by-product gas will be flared, resulting in a large saving even though the controller did not have any influence on the system.

Baseline model 3

Baseline model 3 addresses the limitations of Baseline model 2 by adding another parameter. Similar to Baseline model 1, the model also works with the simulated by-product gas flaring reduction percentage. But, the model uses a regression between the by-product gas flaring reduction and the electricity generation on that particular day.

To construct the regression model, the electricity generated is required over the baseline period. The same data set used to explain Baseline model 2 is used for model 3. Figure 20 illustrates the same data set with the addition of electricity generated by the on-site alternators. The data does not show the controller impact, even though, the electricity generation has now been added.

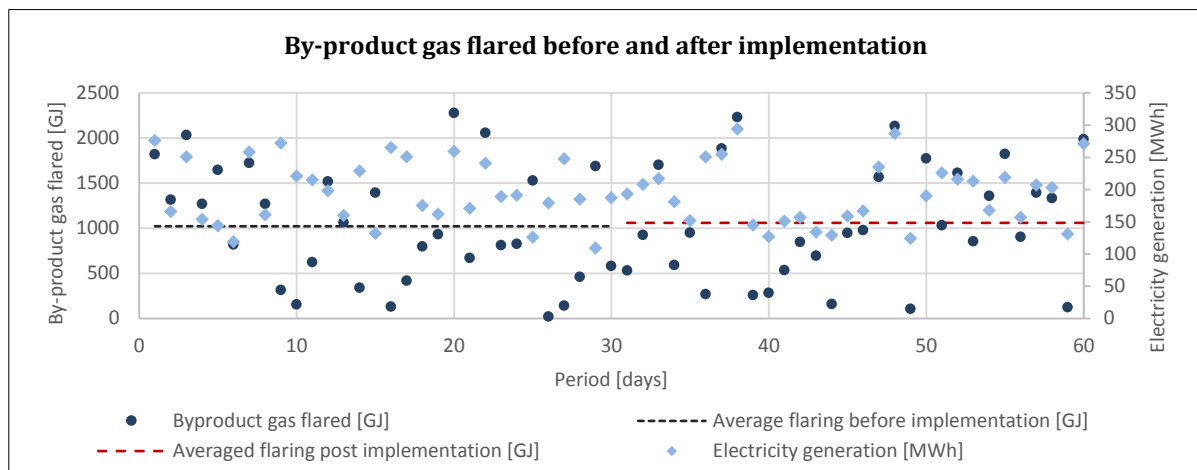


Figure 20: Example of an inconsistent network before and after controller implementation flaring and electricity generation

Similar to Baseline model 2, a reduction factor in by-product gas flared is calculated using simulations. Baseline model 3 incorporates the correlation between the amount of flaring reduction and electricity generation. This correlation is illustrated in Figure 21 using a regression model. The regression model has a negative gradient. The curve indicates that as the electricity generation increases, the flaring reduction factor decreases.

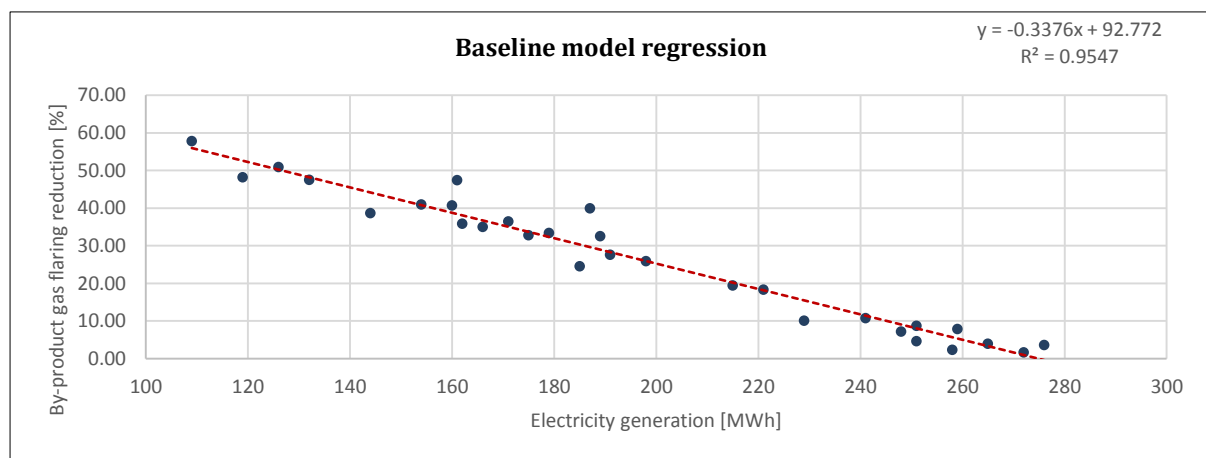


Figure 21: Example Baseline model 3 regression model

This inverse correlation between the controller's influence and electricity generation is the crux of Baseline model 3. It indicates that the controller has the largest impact when the system is operating with a mild to low by-product gas production. It is due to flaring that can be completely avoided. Similarly, the controller has the smallest impact when too much gas is available. It is due to the maximum electricity generation capacity of the being reached with excess by-product gas available.

The routine adjustment is calculated, firstly by determining a by-product gas flaring reduction factor using the regression model. Thus ensuring that a relevant by-product gas flaring reduction percentage is used unlike Baseline model 2 which uses a constant percentage each instance. The regression model is determined with the simulated data. Equation 15 is used to determine the flaring reduction percentage according to the regression model.

$$FS_{reduction} = m * AE_{P,actual} + c \quad (15)$$

Where

$FS_{reduction}$ = By-product gas flaring reduction factor [%]
 $AE_{G,actual}$ = Alternator actual Electricity generation [MWh]
 m = Gradient [%/MWh]
 c = Y-intercept [%]

Once the flaring reduction factor is calculated, the routine adjustment is determined in the same way as in Baseline model 2 (Equation 12). Figure 22 illustrated the routine adjusted by-product gas flaring when compared with the actual by-product gas flaring. It is clear for the days where there were large amounts of flaring, that the routine adjusted flaring does not have those increasing the large flaring.

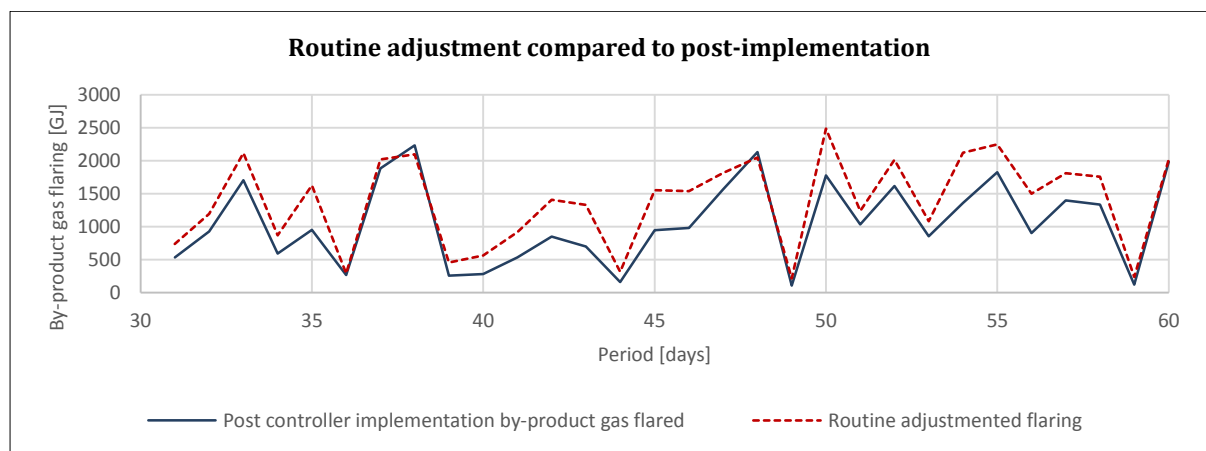


Figure 22: Example of Baseline model 3 routine adjustment and flaring

On the contrary to Baseline model 2, at a point, the routine adjusted flaring is less than the actual. It indicates that the controller had no influence on the system in such cases. This is the benefit of Baseline model 3 compared to model 2. Baseline model 2 can compensate by declaring days where the maximum generation was reached as condonable.

In addition, a scalable regression model can also be used with Baseline model 3. This would prevent the routine adjusted flaring being less than the actual, for instance where the system is oversupplied with gas. The scalable regression model works on the principle of the generation capacity for the instance at which the model is used. Thus the model updates the gradient and y-intercept for each instance.

A comparison between the routine adjusted and actual flaring of Baseline models 2 and 3 is illustrated in Figure 23. Each surface on the graph represents the difference between the routine adjusted by-product gas flared and what was actually flared. The results indicate how the regression model prevents the routine adjusted flaring from being excessive for instances where the system was constrained.

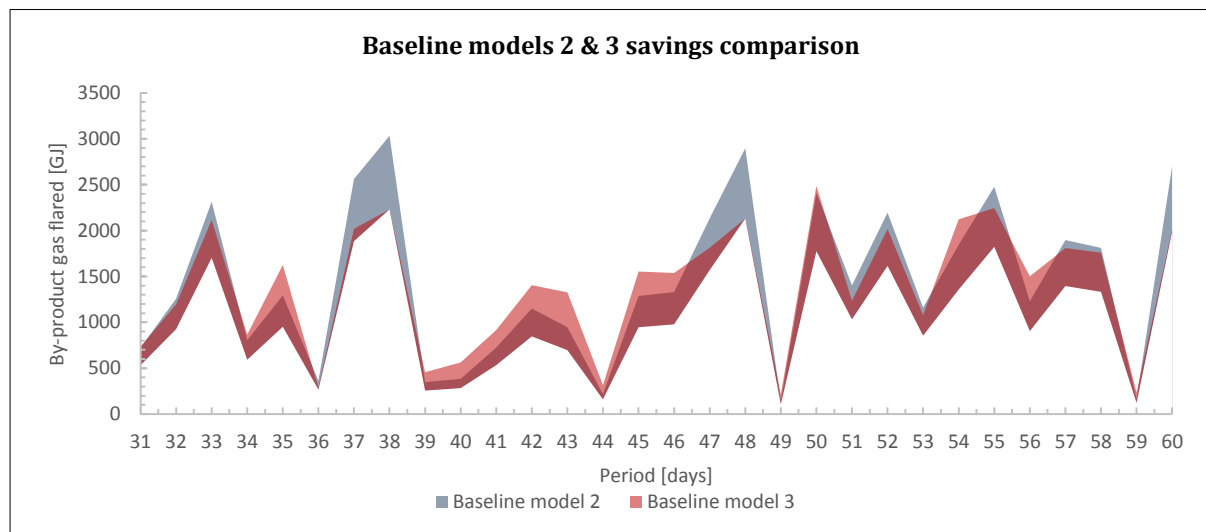


Figure 23: Comparison between actual flaring and routine adjustment of Baseline models 2 and 3

Both Baseline models 2 and 3 have the benefit to alter their routine adjustments according to the system. These models are, however, required for simulations which can lead to discrepancies between the actual system and the mathematical model. Baseline models 4 and 5 are completely based on actual data from the system like Baseline model 1, but have the benefit to adjust according to the system.

Baseline model 4

Baseline model 4 functions on the influence that the controller has in the distribution of by-product gas among gas flared, sent to boilers, and the amount of electricity generation. The controller generates more electricity than the operator, with the same amount of gas flared and sent to the boilers. This concept was explained in Section 3.4.1 and illustrated in Figure 10.

The correlation between the sum of by-product gas flared and sent to boilers to the amount of electricity generated is used. Figure 24 illustrates an example of the regression model between the correlations. This linear regression is then used to determine the routine adjusted electricity generation. Equation 16 is used to determine the routine adjustment for Baseline model 4.

$$BM_{RA} = m * (BS_{E, cap_{utilised}, \Delta t} + FS_{E, \Delta t}) + c \quad (16)$$

Where,

BM_{RA}	= Baseline model routine adjustment [MWh]
$BS_{E, cap_{utilised}, \Delta t}$	= Boilers' steam generation capacity utilised for period Δt [GJ]
$FS_{E, \Delta t}$	= By-product gas energy flared for period Δt [GJ]
m	= Gradient [MWh/GJ]
c	= Y-intercept [MWh]

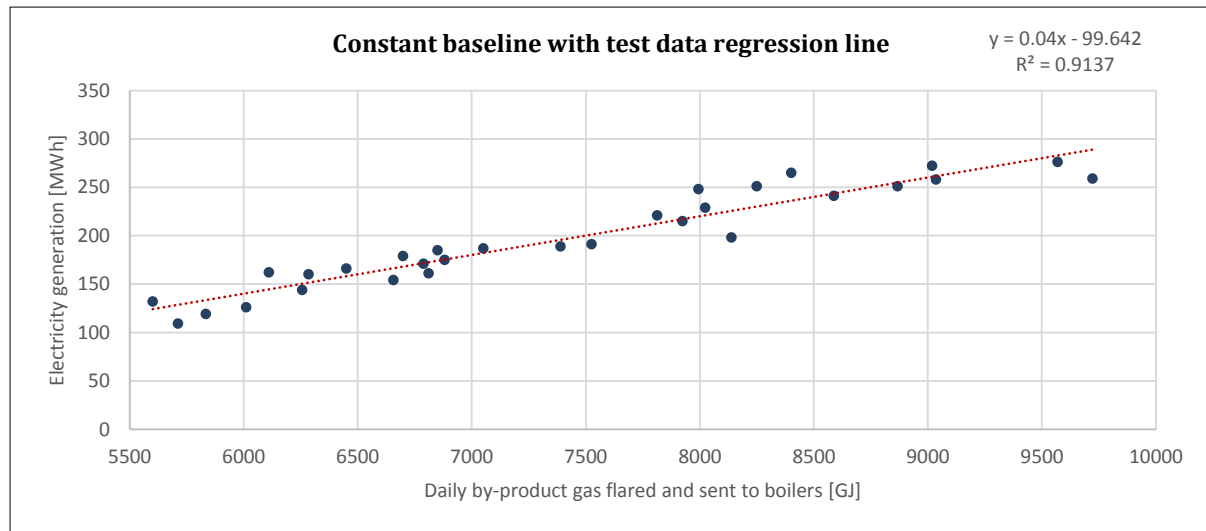


Figure 24: Example Baseline model 4 regression model

In Figure 25, an example is given where the routine adjusted electricity generation was calculated and compared with the actual generation. As the sum of by-product gas flared and sent to the boilers increases, the controller benefit decreases. This correlation is similar to Baseline model 3 and represents the maximum electricity generation capacity being reached.

Baseline models 1 to 5 use by-product gas flared as the mechanism to determine the routine adjustment. By-product gas flared does, however, have more influencing factors than electricity generation. These influencing factors might not be relevant to the controller but will influence the routine adjustment. Baseline model 5 used electricity generation rather than by-product gas flared as the mechanism for the routine adjustment.

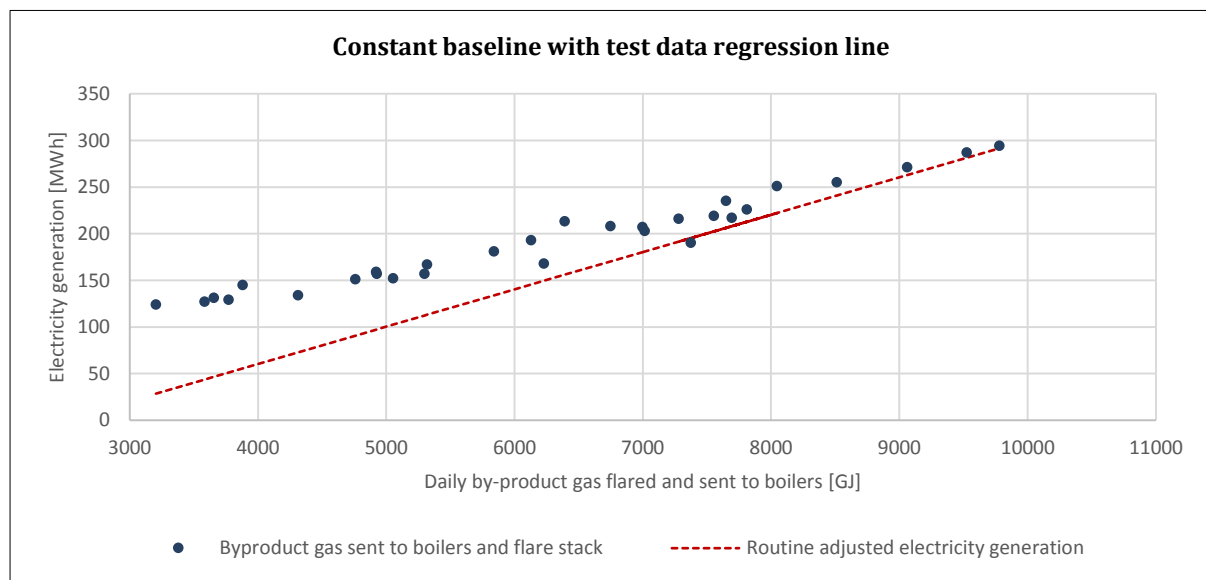


Figure 25: Example of Baseline model 4 routine adjustment and generation

Baseline model 5

Baseline model 5 is similar to model 2 as it is a constant factor baseline model. But, where Baseline model 2 uses by-product gas flared, Baseline model 5 uses electricity generation. Additionally, Baseline model 5 is constructed using data pre- and post-implementation. The model can therefore only be constructed after the controller has already been implemented and has been successfully operating for at least a month.

The model uses a benefit factor determined from data with similar operating system conditions. Thus, unlike the other baseline models, a month before and a month after is used as the baseline

period. For this baseline model, it is assumed that the by-product gas and on-site power generation systems remained constant over the baseline period.

The constant electricity generation factor is calculated using Equation 17. The equation determines the portion of electricity generated due to the controller. It is determined with the average electricity generation before and after the controller was implemented.

$$BM_{AF} = \frac{avg_{BP_{ACI}}(AE_{G, cap_{utilised}, \Delta t}) - avg_{BP_{BCI}}(AE_{G, cap_{utilised}, \Delta t})}{avg_{BP_{ACI}}(AE_{G, cap_{utilised}, \Delta t})} \quad (17)$$

Where,

$$\begin{aligned} BM_{AF} &= \text{Baseline model adjustment factor} \\ AE_{E, cap_{utilised}, \Delta t} &= \text{Alternators' electricity generation capacity utilised for period } \Delta t \text{ [GJ]} \\ avg_{BP_{ACI}} &= \text{Average for baseline period after controller implementation} \\ avg_{BP_{BCI}} &= \text{Average for baseline period before controller implementation} \end{aligned}$$

The routine adjustment is calculated with this benefit factor as seen in Equation 18. In the equation, the routine adjustment factor determines the electricity generation that should have been generated without the implementation of the controller. Thus the routine adjusted electricity generation is less than what is actually generated after the controller has been implemented.

$$BM_{RA} = AE_{G, cap_{utilised}, \Delta t} * \left(\frac{100 - BM_{AF}}{100} \right) \quad (18)$$

Where,

$$\begin{aligned} BM_{RA} &= \text{Baseline model routine adjustment [MWh]} \\ AE_{G, cap_{utilised}, \Delta t} &= \text{Alternators' electricity generation capacity utilised for period } \Delta t \text{ [MWh]} \\ BM_{AF} &= \text{Baseline model adjustment factor} \end{aligned}$$

Figure 26 illustrates an example of electricity generation before and after a controller was implemented. The electricity generation increased after the controller was implemented. The benefit is evident in Figure 26. This would be the case if the relevant systems remained constant before and after implementation. If there are days where the system did not remain constant, these days should be seen as condonable.

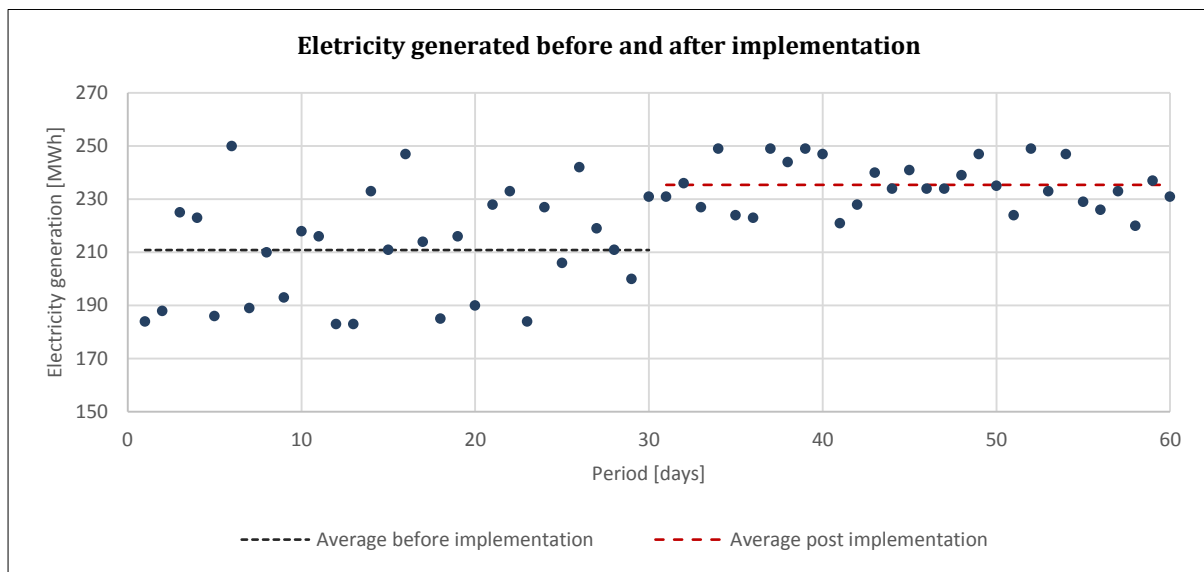


Figure 26: Example generation before and after implementation

An example of the routine adjusted generation compared with the actual generation is illustrated Figure 27. As expected, the routine adjusted generation is consistently below the actual generation. This routine adjustment can now be used even though the system changes because the benefit of the controller would remain the same.

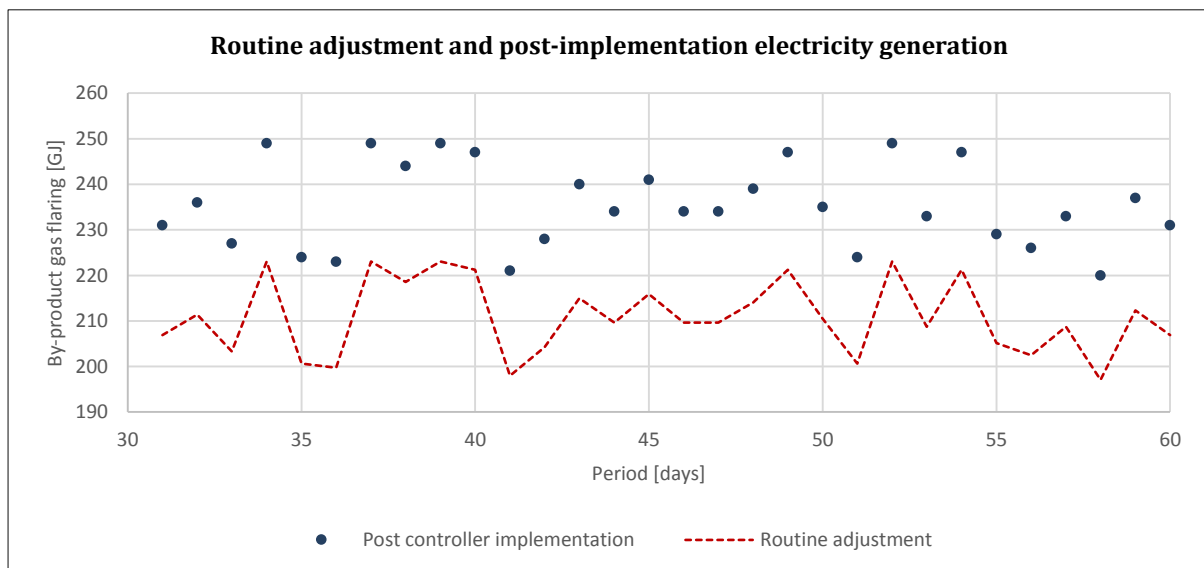


Figure 27: Example of Baseline model 5 routine adjustment and generation

Summary

The different routine adjustments of each baseline model are compared in Table 5. The baseline model type, data required and baseline model equations are compared with each other. Additionally, graphs are used to illustrate raw data before and after the controller was implemented and how the routine adjustments use this data to determine a benefit.

Baseline model 1 is a constant model which requires a consistent system with little to no noise to accurately determine the controller benefit, where Baseline models 2 to 5 can determine an accurate benefit with noise present. Baseline model 2 uses a constant flaring reduction factor but lacks the ability to compensate for instances where maximum electricity generation was reached. A flaring reduction factor is calculated using a simulation on data before the controller was implemented.

The electricity generation capacity is compensated for in Baseline model 3 using a regression model between the flaring reduction factor and electricity generation based on simulated data. Both Baseline models 2 and 3 required a simulation model. Possible discrepancies between the simulation model and actual system led to Baseline model 4 and 5 which are constructed from actual data.

Baseline model 4 is a regression model using the benefits of the controller increasing the electricity generation from surplus by-product gas. Finally, Baseline model 5 is the only model not using by-product gas flared. The model uses a benefit electricity generation factor. Additionally, Baseline model 5 is the only model using a different baseline period. Baseline model 5's baseline period is not only before implementation but also post.

Each Baseline model uses a different mechanism to determine the routine adjustment. The five mechanisms developed has its own set of advantages and disadvantages. Before a baseline model is selected the available data and system needs to be evaluated. Each of the routine adjustment mechanisms is evaluated and compared with each other in Chapter 4. The comparisons are made on actual measurements from the case study.

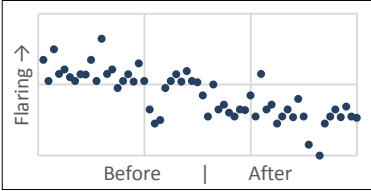
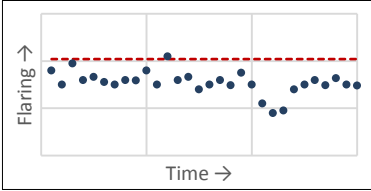
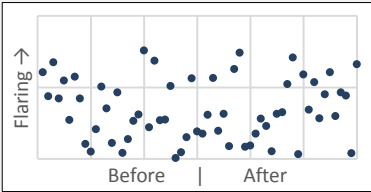
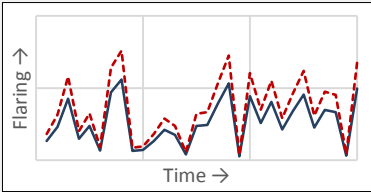
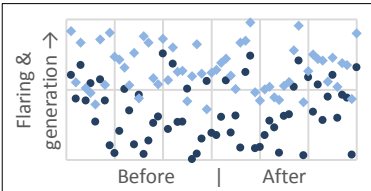
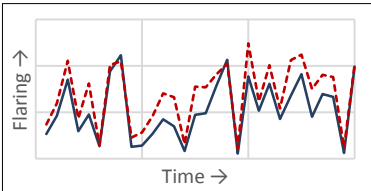
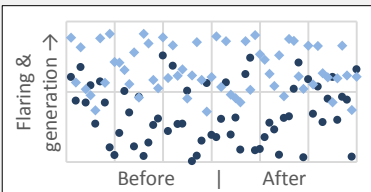
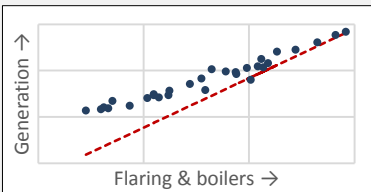
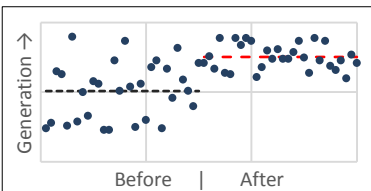
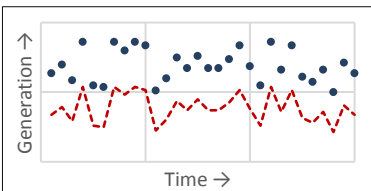
Baseline model	Baseline model type	Data required	Baseline model mechanism (equations)	Data before and after implementation	Routine adjusted profile
1	Constant	By-product gas flared	$BM_{RA} = avg_{BP}(FS_{E,\Delta t})$		
2	Constant factor	By-product gas flared	$FS_{reduction} = \frac{avg_{BP}(FS_{E,\Delta t}) - avg_{BP}(FS_{E_{sim},\Delta t})}{avg_{BP}(FS_{E,\Delta t})}$ $BM_{RA} = FS_{E,\Delta t} * \left(\frac{100}{100 - FS_{reduction}} \right)$		
3	Regression & constant factor	By-product gas flared, and electricity generation	$FS_{reduction} = m * AE_{P,actual} + c$ $BM_{RA} = FS_{E,\Delta t} * \left(\frac{100}{100 - FS_{reduction}} \right)$		
4	Regression	By-product gas flared, by-product gas sent to boilers, and electricity generation	$BM_{RA} = m * (BS_{E,caputilised,\Delta t} + FS_{E,\Delta t}) + c$		
5	Constant factor	Electricity generation	$BM_{AF} = \frac{avg_{BP_{ACI}}(AE_{G,caputilised,\Delta t}) - avg_{BP_{BCI}}(AE_{G,caputilised,\Delta t})}{avg_{BP_{ACI}}(AE_{G,caputilised,\Delta t})}$ $BM_{RA} = AE_{G,caputilised,\Delta t} * \left(\frac{100 - BM_{AF}}{100} \right)$		

Table 5: Baseline models routine adjustments overview

3.5.6 Saving quantification

Quantifying the savings reflects the actual benefit of the controller. The savings of this controller can be reflected in either energy (GJ), electricity (MWh), or a monetary value (rand). Of the three units, money has the largest impact. People work with high amounts of energy and electricity on a daily basis which generally becomes normalised to the enormity of the units. Contrary to belief, money will always reflect the enormity.

The routine adjustment is done to determine how the system would have reacted in the case that the controller was not implemented. Therefore, the absolute difference between the routine adjustment and actual is the benefit of the controller. Equation 19 is used to determine the control benefit.

$$CB = abs(BM_{RA} - Actual) \quad (19)$$

Where,

CB = Controller benefit [MWh]/[GJ]

BM_{RA} = Baseline model routine adjustment [MWh]/[GJ]

$Actual$ = Actual performance after controller implementation [MWh]/[GJ]

Baseline model 1 to 3 determines the routine adjustment in the amount of by-product gas flared reduced in GJ, where Baseline model 4 and 5 additionally determines electricity generated in MWh. Resultantly, the control benefit is calculated in the same units. Both the by-product gas volume and electricity generation needs to be quantified in a monetary value.

The reduction in by-product gas flared is a result of additional electricity generation (see Figure 10). Thus if the control benefit is calculated in flaring reduction units, it must first be converted to additional electricity generation. The conversation from energy flared to electricity generated is done using the boilers' and alternators' efficiencies. Equation 20 should be used for the conversion.

$$AE_{G,CB,\Delta t} = \frac{FS_{E,CB,\Delta t}}{\eta_B \eta_A} \quad (20)$$

Where,

$AE_{G,CB,\Delta t}$ = Alternator electricity generation controller benefit for period Δt [MWh]

$FS_{E,CB,\Delta t}$ = By-product gas energy flared controller benefit for period Δt [GJ]

η_B = Boilers combined efficiency [GJ/tonne steam]

η_A = Alternators combined efficiency [tonne steam/MWh]

The additional electricity generation is then converted to a monetary value using the Eskom tariffs. Eskom tariffs generally consist of four different components for industrial plants such as steel producing facilities. These components include the TOU, affordability subsidy, electrification and rural subsidy charge, and reactive energy charge.

The TOU components needs to be constant because the additional electricity generation benefit is an accumulation across the day. Thus, TOU is made constant with a weighted TOU tariff as seen in Equation 21.

$$WET_D = \sum_{TOU = \text{peak}, \text{standard}, \text{off-peak}} \left(\frac{Hours_{TOU}}{24} \right) ET_{TOU} \quad (21)$$

Where

WET_D = Weighted electricity tariff for day type [R/MWh]
 D = Day type; weekday, Saturday or Sunday
 $Hours_{TOU}$ = Hours per time of use tariff [h]
 ET_{TOU} = Eskom electricity tariff for time of use [R/MWh]
 TOU = Time of use; peak, standard and off-peak

The complete Eskom tariff is the sum of the weighted TOU component, affordability subsidy and electrification, and rural subsidy charge. Thus Equation 22 should be used as the electricity rate. The reactive energy charge is not incorporated due to the instrumentation needed to measure parameters to determine the power factor as required.

$$ER = (WET_D + C_{AS} + C_{ERSC}) \quad (22)$$

Where

ER = Electricity rate [R/MWh]
 C_{AS} = Eskom affordability subsidy contant [R/MWh]
 C_{ERSC} = Eskom electrification and rural subsidy charge [R/MWh]

3.5.7 Non-routine adjustments

Non-routine changes on the by-product gas network of the on-site power generation plant influence the validity of the routine adjustments. Non-routine adjustments will then need to be made to the baseline models to ensure accurate saving quantification. It is important to discuss any of these types of changes between the relevant stakeholders. An example of a non-routine change to the system is the addition of an alternator or boiler.

3.6 Procedures to ensure sustainability

Project sustainability is key to a successful, continuous refining controller. The inconsistent nature of the by-product gas network forces continual controller updates. If the controller is not updated to accommodate system changes, it would result in a reduction in performance or render the controller unable to operate. Thus, resulting in the operators not using the controller anymore and the project fading away.

The project sustainability consists of continuously tracking and reporting the performance of the controller. A reoccurring report indicating the performance must be sent to the responsible parties. These parties must typically include the operators and their managers. Depending on whether a third party was involved and would remain involved, a performance tracking report must be sent to them as well.

The report must be short, to the point, fast and easily analysed. If not, the responsible parties who are supposed to ensure that the project is performing would lose interest and stop evaluating the reports. Additionally, the reports must have a component that draws the user to open and analyse it. This drawing component can be anything from important information to visually pleasing graphs.

The report must contain all the relevant data required to update the controller adequately if needed. It is important that the report includes the data which influences the controller performance. This data consists of the boilers' gas flows, flaring, gas holder levels and any other significant energy consumer that has an influence on the by-product gas network or on-site power generation plant.

3.7 Conclusion

A three-step methodology was developed to generically identify a suitable iron and steel manufacturing facility for the controller, design and simulator, implement the controller and finally measure controller benefit and ensure that the project is sustainable. Identifying a suitable facility requires prerequisite infrastructure, appropriate saving scope and system constraints accommodating the controller. If any one of the previously mentioned components is not satisfied by the facility, the facility is not adequate for the controller.

The following step is to design the controller and use a step or continuous controlling method. The step control method keeps the boiler and alternator stable by adjusting the alternator set point by intervals, where the continuous control actively adjusts the set point of the alternators according to a function of the gas holder level. The selected control design then needs to be refined using a simulation based on the actual facility's infrastructure.

Once the appropriate parties have agreed on the design of the controller, the controller must be implemented. Implementation must preferably be done by directly coding the controller into the controlling SCADA. Otherwise, providing the operator with an additional computer with live control instructions or print out of a set of rules for the process controllers to operate by.

Adequate time after implementation needs to be spent with the operators to tweak the controller according to their preference. It is important to keep their buy-in on the project as they will be the ones ensuring sustainable use of the controller. Only after the operators are satisfied, should a performance tracking report be built. The report should clearly indicate the benefit of the controller on a daily basis.

Sustainability of the controller is based on the project performance tracking report periodically reaching allocated responsible parties. The measuring method needs to be suitable for the facility. Five different baseline models are discussed as each addresses a different measurement complication.

Chapter 4 – Case study



Figure 28: Worker at steel plant⁴

Controller implemented on a case study

⁴ Turkish steel producers association, “Turkish steel industry in 2015”, [Online]. Available: www.celik.org.tr/en/

4.1 Introduction

Chapter 4 validates the methodology developed in Chapter 3 by applying it to a case study. A detailed overview of the case study is presented and used throughout the chapter. Each step of the methodology from Chapter 3 is applied chronologically to the case study. A system specific controller is designed and implemented based on system constraints.

Two months' data, after the controller implementation, is used to determine the actual benefit. The controller benefit is calculated using five baseline models. The baseline period is one month before controller implementation. Finally, the chapter concludes with a project sustainability strategy to ensure continuous performance.

4.2 Case study overview

4.2.1 Facility overview

An iron and steel manufacturing facility located in South Africa was used for the case study. The facility, similar to the rest of the industry, is forced to reduce production costs due to deteriorated market conditions (Section 1.2). In this section, an overview of the facility and comprehensive descriptions of the gas and steam networks, as well as the control of these sections is presented.

The facility produces steel with the BOS process (Section 1.3). Iron is, therefore, produced by a blast furnace and steel using a BOF. Figure 29 holistically illustrates the sections of the case study. Coke and sinter are produced by the facility and used among other raw materials in the blast furnace to produce liquid iron.

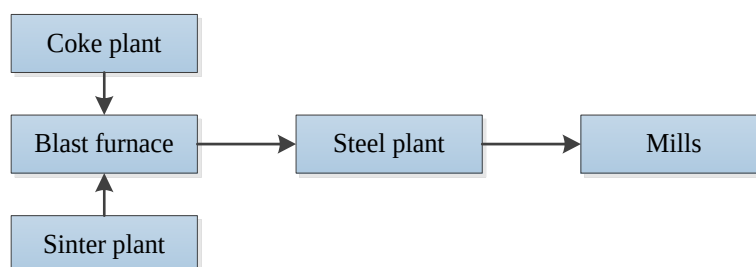


Figure 29: Case study plants integration overview

Torpedo ladles transport the liquid iron from the blast furnace to the steel plant. At the steel plant, three BOFs are used to turn the iron into steel. The steel grade is tailored with the ladle furnaces and degassers. Finally, the continuous casters cast the molten steel into blooms which are rolled and formed in the mills to the client's product.

The case study has an energy distribution and management plant. It is their responsibility to supply and balance the compressed air, nitrogen, steam, gas, etc. to the facility. The energy distribution section consists of a control room with shift operators and a maintenance department. The maintenance department is responsible for the availability of each network.

Advantages of having an energy distribution section include a reduced load on plants allowing more focus on production. Plants receive required gas and other auxiliaries without having to be concerned about availability. The energy distribution section, resultantly, improves the overall facility efficiency by relieving the plants from managing their energy and auxiliary supply and demands.

Additionally, the energy distribution section can optimise gas and auxiliary distribution. The opportunity is due to the holistic overview of the section. Having a holistic overview allows the section to apply interplant energy efficiency initiatives. Personnel from the case study emphasised that each plant on the facility operates in an isolated fashion. This behaviour leads to interplant energy saving initiatives having a low success rate.

4.2.2 Gas network overview

A BOS iron and steel manufacturer produces BFG, COG and BOSG. These gases, if reclaimed, are used as a by-product (see Section 1.4). The case study reclaims BFG and COG at the blast furnace and coke ovens. An extended payback period rendered a BOSG reclaiming system as unfeasible. Locally sourced natural gas is used as a supplement to add where by-product gas is unable to supply the required demand. Natural gas is supplied upon request from a supply line passing the works.

Figure 30 illustrates the gas network of the plant, separating the network into three sections. These sections include gas supply, gas management and plant consumption, and steam supply and on-site power generation. The gas supply section consists of the coke ovens, blast furnace and the natural gas line. COG, BFG and natural gas are the fuel gases supplied throughout the facility (see Section 1.4).

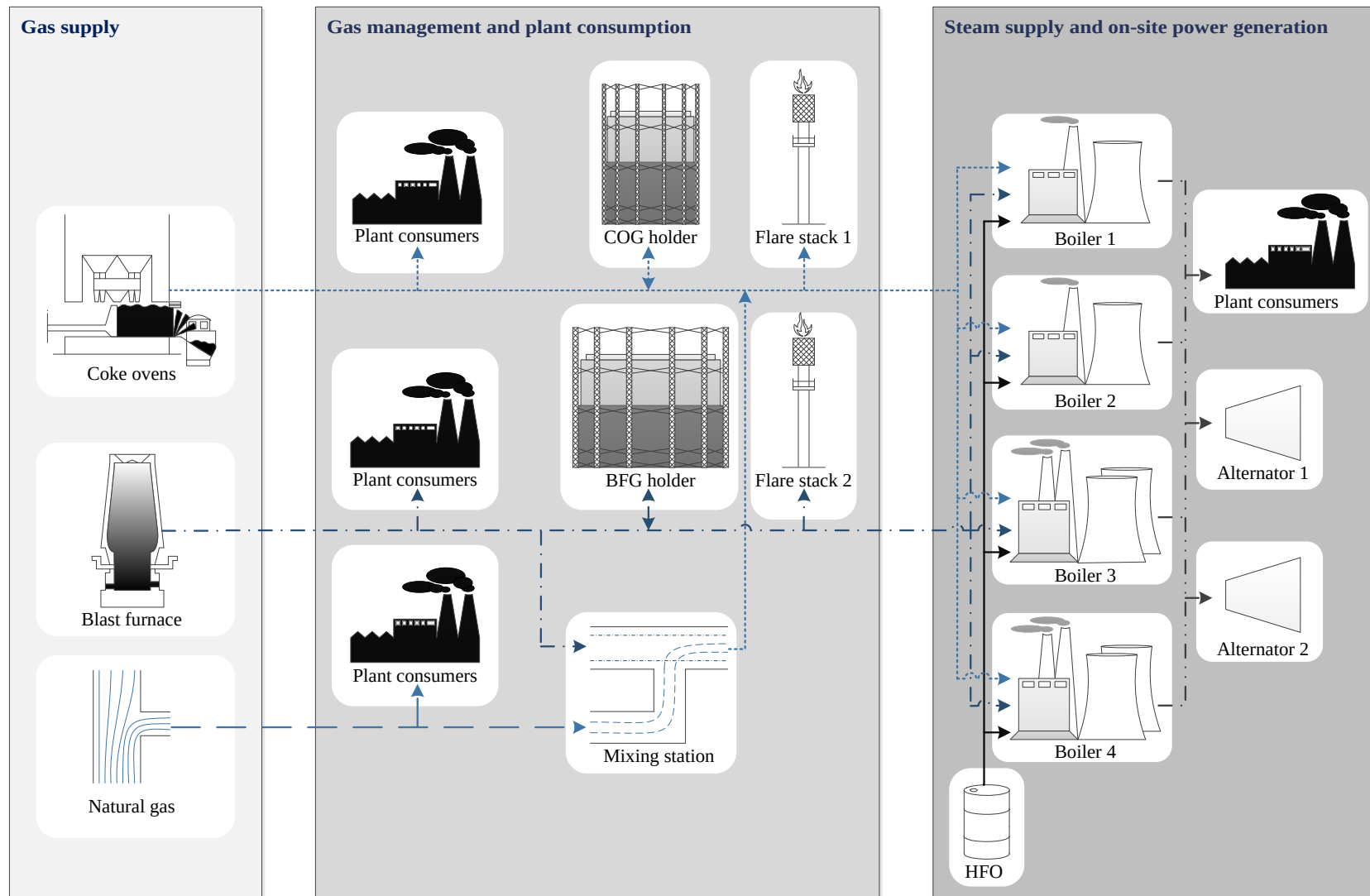


Figure 30: Case study gas network overview

The fuel gases are distributed among consumers and managed with a network consisting of flare stacks and gas holders. Both the COG and BFG networks have a flare stack and gas holder each. The gas holders act as buffers for imbalances caused by by-product gas production and consumption differences. Flare stacks relieve the network from excess by-product gas. A shortage of by-product gas leads to use of natural gases.

It is the responsibility of the operators at the energy distribution section to flare and use as little by-product and natural gas as possible. Each fuel gas is supplied to consumers aiding in the iron and steel making process. Sections 4.2.3, 4.2.4 and 4.2.5 elaborates on each of these gases. COG is considered, by the facility, as a more valuable gas than BFG. This is due to the facility producing COG which has 4.5 times more energy per volume than BFG.

A shortage of COG in 2005 forced the facility to commission a mixing station. The mixing station combines BFG with natural gas to produce a product similar to COG. A Wobbe analyser provides the operator with the mixing ratios. The operator strives to produce a gas with a similar WI than COG when mixing. The mixed gas is fed directly into the COG line. Mixed gas allows for the use of less natural gas during instances of a shortage in COG but sufficient BFG.

Mixed gas does however, not meet the same characteristics as COG. This drawback is due to COG containing too many impurities. It is impossible for the Wobbe analyser to measure the WI of the COG accurately. The inaccurate WI measurements result in wrong mixing ratios producing an inferior gas. Continuous complaints about the COG consumers led to mixed gas being avoided at all costs.

By-product gas is also used to generate steam. Plants use steam in the iron and steel manufacturing process as well as the alternators to generate electricity. Steam turbines and alternators generate electricity. The facility has a dedicated on-site power generation plant consisting of four boilers and two alternators. Steam supply has a base load consisting of the plant consumers and emergency electricity load.

The facility established an energy electricity load due to frequent power outages from Eskom. These power outages disrupted production processes. The emergency electricity load comprises of a supply of electricity to critical plant sections. The operation can continue with only these sections. Thus, if the facility faces a power outage, these critical sections reduce the impact on production.

Either one of the two alternators need to generate the emergency load. The alternators will trip if neither one of them are producing more electricity than the emergency load during a power outage. Unlike other plants, HFO is used instead of natural gas for instances of by-product gas shortages. HFO is avoided at all times because it is significantly more expensive than by-product gas.

The emergency electricity load consists of the electricity required to keep critical components of the plant running during a power outage. Either one of the two alternators should generate more than the emergency electricity load. If not, and should the plant suffer a power outage, the alternator would trip. The facility generates electricity in sync with Eskom. Thus the generation phase of Eskom and the alternators are the same.

Figure 31 illustrates a holistic energy balance regarding COG, BFG and natural gas for 2013 to 2016. The study focuses on the reduction of by-product gas by increased electricity generation. Thus the energy balance includes plant consumers, the process in the iron and steel manufacturing, the boilers and energy flared. The data presented is in monthly averages annually.

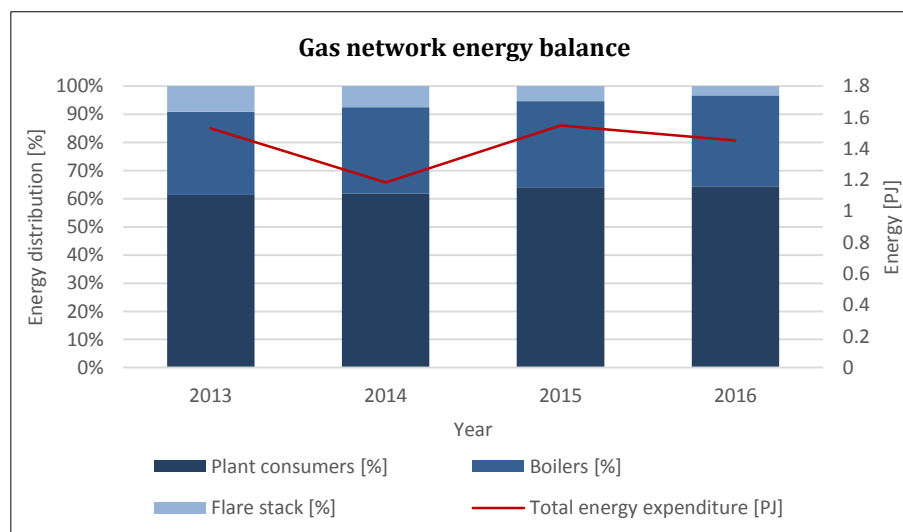


Figure 31: Case study gas network energy balance and average monthly energy expenditure for 2013 to 2016

The iron and steel manufacturing process consumed the most substantial portion being 60% to 65% of energy. Secondly, the boilers which consumed slightly above 30% of the fuel gas energy. The smallest portion, 2.5% to 10%, of energy is flared. The average monthly energy

expenditure remained relatively constant at 1.4 PJ to 1.5 PJ except for the year 2014. In 2014, the average monthly expenditure dropped to 1.2 PJ due to a blast furnace reline.

The energy balance revealed that the facility reduced by-product gas flaring by 7.5% in the four years. A reduction of this consistency and magnitude indicates that the facility is actively focusing on flaring reduction. The facility will, therefore, be more likely to accommodate a project like the one in this study, especially if the facility is forced to reduce the current production costs.

A comprehensive breakdown of the COG, BFG, natural gas, and steam network, as well as the energy management operation is provided in the sections that follow. Similar to the holistic energy balance, each network is analysed based on the years 2013 to 2016. Four years of data is used to determine whether possible trends can be seen to predict energy distributions for 2017.

4.2.3 COG network

The coke making process produces COG. Steam turbines power exhausters which extract the COG from the ovens. Once out of the ovens, COG gas is cleaned at the by-product's plant. The plant removes impurities such as naphthalene and tar within the gas. However, the by-product's plant does not remove enough of the impurities due to improper maintenance rendering the plant in a subordinate condition.

The impurities in the COG result in higher maintenance costs. These costs are due to naphthalene clogging pipes and injector nozzles. Increased downtime and maintenance costs led to some plants preferring natural gas. Figure 32 illustrates the COG distribution network. COG is supplied to the mills, sinter plant, several workshops, the coke ovens itself, boilers, gas holder and a flare stack.

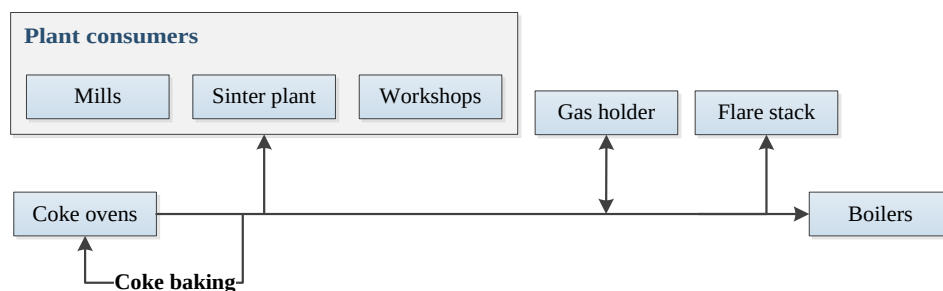


Figure 32: Case study detailed COG distribution and consumer network

The gas holder regulates the network pressure at 14 kPa and the gas holder has a capacity of 15 000m³. The operation limits restrict the usable capacity from 15 000m³ only 11 250m³ (see Section 2.4.1). The high-high and low-low of the holder is 75% and 15% respectively. Thus the holder is operated between 2 250m³ and 11 250m³. Plant personnel complain about the COG holder being too small and not having sufficient buffer capacity. The holder can rise and fall at its fastest in about ten minutes.

Figure 33 illustrates the average monthly energy balance for COG from 2013 to 2016. The balance includes the plant consumers, boilers and flare stack. The most significant portion, 50% to 60% of COG is used in the plant in the iron and steel manufacturing process. The second largest portion, 40% to 45%, is consumed by the boilers. Less than 2.5% of COG is flared.

COG monthly production decreased from 2013 to 2016 by 200 TJ. The reduction is due to less operational coke ovens. A combination of lost skills and mismanagement led to a significant portion of the coke plant being damaged. In 2015, a part of the plant was shut down to commence with repairs. The repairs are set to be completed in 2017. Thus the reduction in COG is due to fewer coke ovens available.

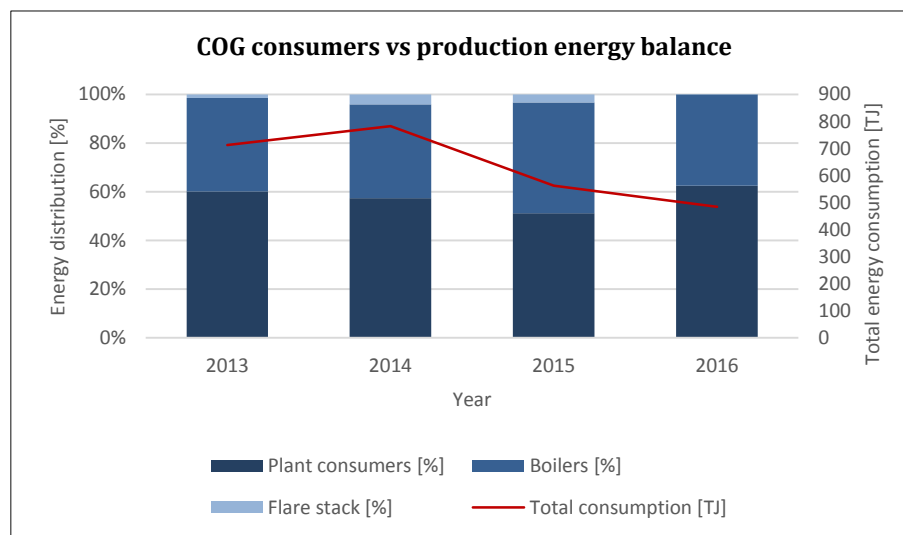


Figure 33: Case study COG energy balance and monthly average energy expenditure for 2013 to 2016

Additionally, the monthly portion of COG reduced for roughly 15 000 TJ in 2013 to 2015 to 200 TJ in 2016. The reduction is due to less COG being available and strict Key Performance Indicators (KPIs) being implemented against COG flaring. Figure 34 illustrates the energy

balance of COG among plant consumers. Significant COG consumers influence the integrated by-product gas network.

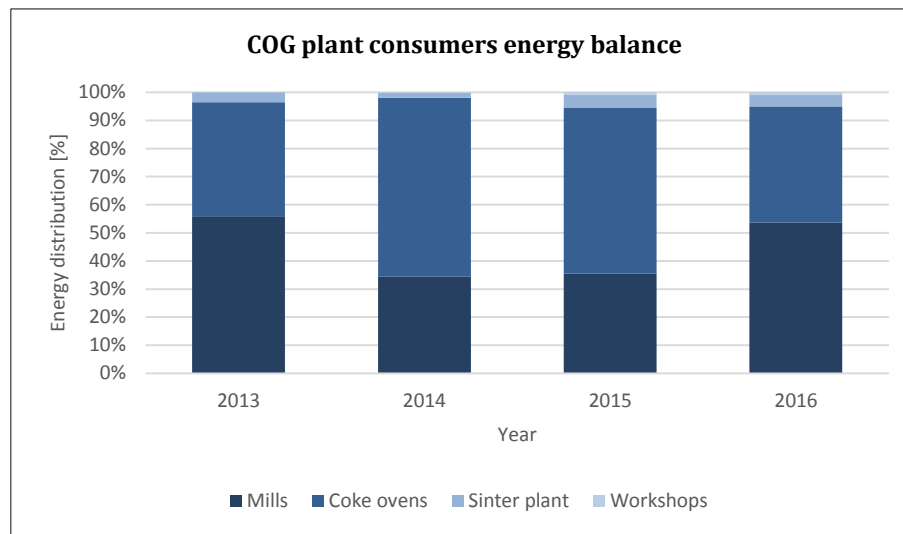


Figure 34: Case study COG detailed energy distribution among gas consumed plants for 2013 to 2016

The coke ovens and mills are the two largest consumers. Whereas, the sinter plant and workshops consumes too little COG to influence the network. The mills have the largest influence on the network due to the coke ovens consuming proportionally to production. In the case of the mills, no correlation exists. Therefore, the mills reducing COG demand results in a surplus of COG. The operators control the COG with the mills as the highest priority.

4.2.4 BFG network

The iron making process produces BFG gas. BFG is reclaimed at the top of the blast furnace as produced. Unlike COG, BFG is clean and can be used immediately after being reclaimed. Figure 35 illustrates the BFG distribution network. BFG is supplied to the coke ovens, the blast furnace stove, a gas plant, the boilers, gas holder and flare stack. BFG has fewer consumers due to its inferior energy contents. The facility produces COG with 4.5 times more energy per volume than BFG.

The BFG gas holder regulates the network pressure at 10 kPa to 12 kPa, and the gas holder has a capacity of 80 000m³. The operation limits restrict the usable capacity from 80 000m³ to 64 000m³. Compared to the COG gas holder, the BFG gas holder is significantly larger. The

difference is due to the plant producing more BFG than COG. Additionally, the BFG gas holder has the ability to store COG, but this functionality is not used.

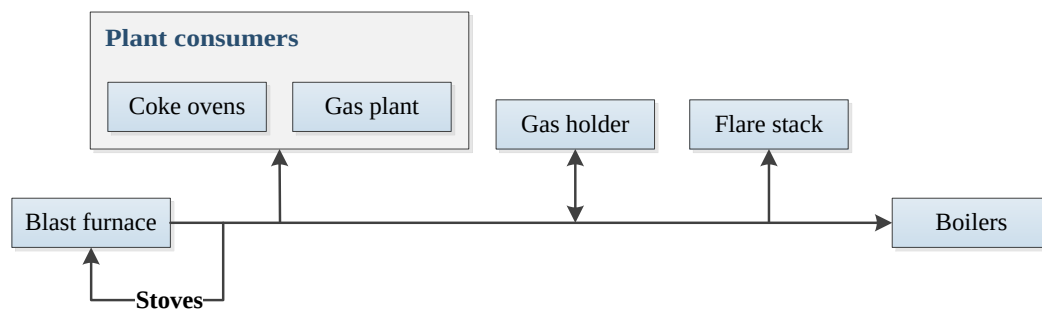


Figure 35: Case study detailed BFG distribution and consumer network

Figure 36 illustrates the average monthly energy balance for BFG from 2013 to 2016. The balance included the plant consumers, boilers and flare stack. The most significant portion, at 60% of BFG, is consumed by plants in the iron and steel manufacturing process. The second largest share, 20% to 35%, is used by the boilers. The smallest portion of BFG is flared between 7.5% and 18.5%.

BFG monthly production remained constant at 750 TJ except for the year 2014. In 2014, the BFG production decreased to 330 TJ due to the blast furnace relining. The relining caused a four-month shutdown for the furnace. Production is however, set to remain in the vicinity of 750 TJ in 2017. The BFG flaring reduced from 125 TJ to 50 TJ from 2013 to 2016. The personnel agrees that only energy awareness caused the reduction.

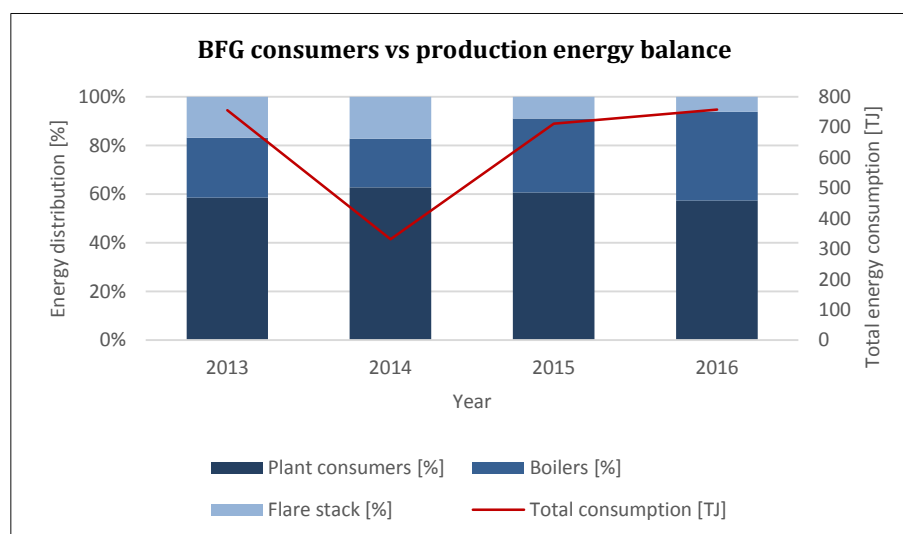


Figure 36: Case study BFG network energy balance and average monthly energy expenditure for 2013 to 2016

Figure 37 illustrates the energy balance of BFG between the plant consumers. The blast furnace stoves are the largest consumers at a relatively constant 60%. The coke ovens follow with 40% followed by the gas plant at less than 2.5%. Stoves use BFG to heat up cold blast air for the iron making process. Thus, the amount of BFG used by stoves generally remains proportional in iron production.

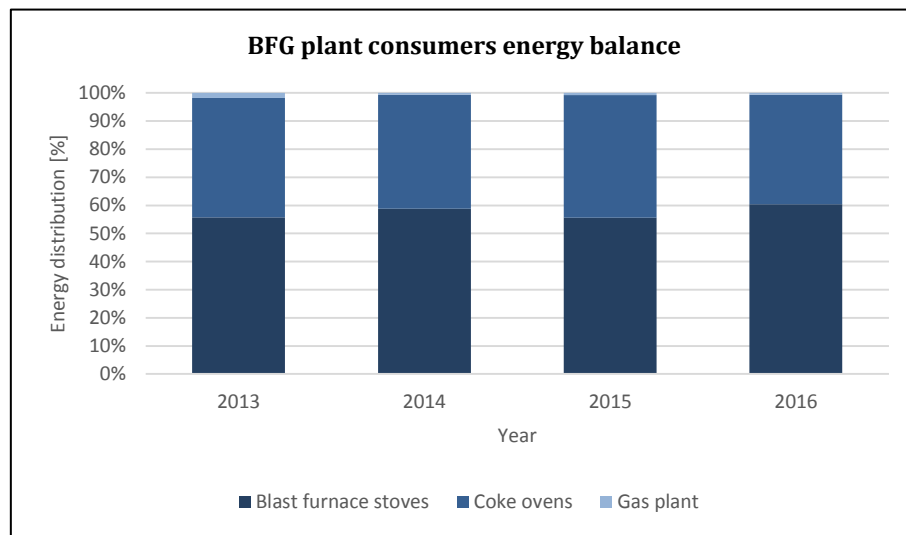


Figure 37: Case study BFG detailed energy distribution among gas consumed by plants for 2013 to 2016

The coke oven also consumes BFG at a relatively constant rate. It takes about one to three hours to transition between fuel gases for the coke ovens. Thus transitions are only made when critical. On the other hand, the boilers have a much higher rate of change between fuels. Therefore, the boilers can be used second to the gas holders to buffer by-product gas imbalances.

4.2.5 Natural gas network

Natural gas is only used for instances of by-product gas shortages. It costs the facility significantly more to use natural gas compared to by-product gas. Figure 38 illustrates the natural gas network. Natural gas is supplied to the mills, coke ovens, steel plant, workshops and service points, and the mixing stations. The workshops and service points are the only consumers of natural gas which do not also have a by-product gas supply.

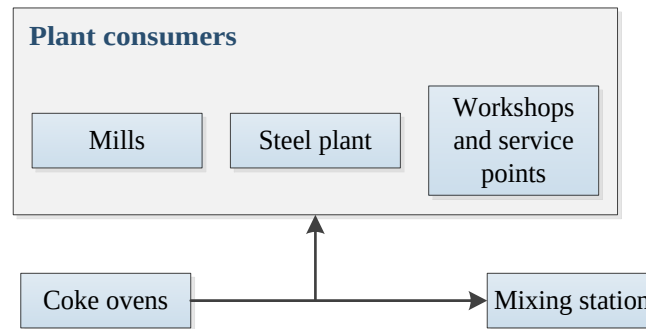


Figure 38: Case study detailed natural gas distribution and consumers network

The mixing station, as mentioned in case study overview, is avoided at all times. Figure 39 illustrates the average monthly energy balance for natural gas from 2013 to 2016. The amount of natural gas mixed reduced from 2013 to 2014 by 25% but then increased from 2015 to 2016 by 10%. These fluctuations are due to the plant operating unpredictably. For instance, an inconsistent supply of COG puts the gas holder at risk, forcing operators to add mixed gas to the network.

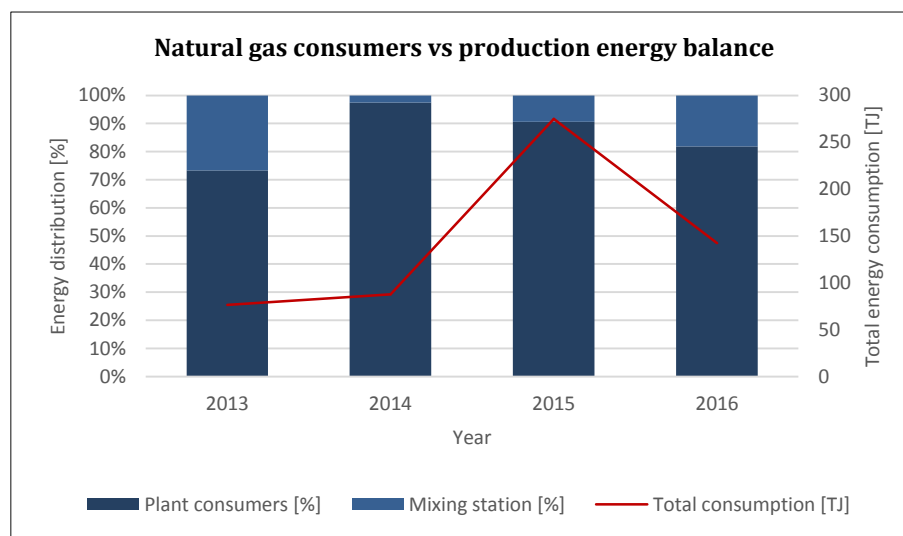


Figure 39: Case study natural gas network energy balance and average monthly energy expenditure for 2013 to 2016

In 2015, the monthly natural gas consumption increased to 275 TJ from 90 TJ in 2014. The increase is due to the sudden drop in COG during 2015. However, from 2015 to 2016 the natural gas consumption dropped to 150 TJ with similar COG production rates. This reduction indicates that the plant managed to operate more efficiently on low COG production rates.

In Figure 40, the energy balance among the natural gas plant consumers for 2013 to 2016 is presented. The largest consumer is the mills consuming 87.5% to 90%, followed by the steel

plant at 10% to 20%. The least significant consumer is the workshops and service points at less than 2.5%. The mills consumption decreased across the four years. The reduction is due to the facility driving for the mills to operate on as much COG and little natural gas as possible.

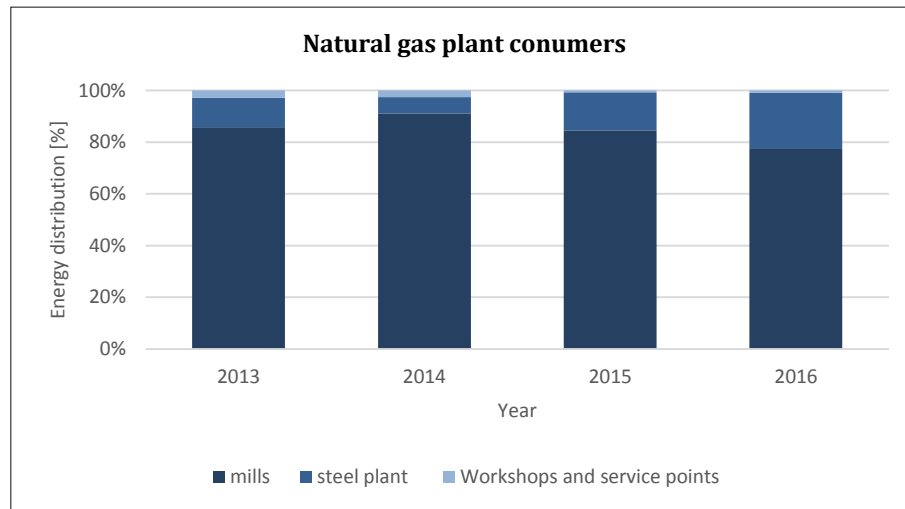


Figure 40: Case study natural gas detailed energy distribution among gas consumed by the different plants for 2013 to 2016

4.2.6 Steam network

The facility has a fully integrated steam network to supply steam to numerous consumers. However, the boilers have additional capacity apart from the baseload. The additional capacity allows for excess by-product gas to generate electricity. Figure 41 illustrates the mass balance of the average monthly steam consumption among plant consumers and the alternators.

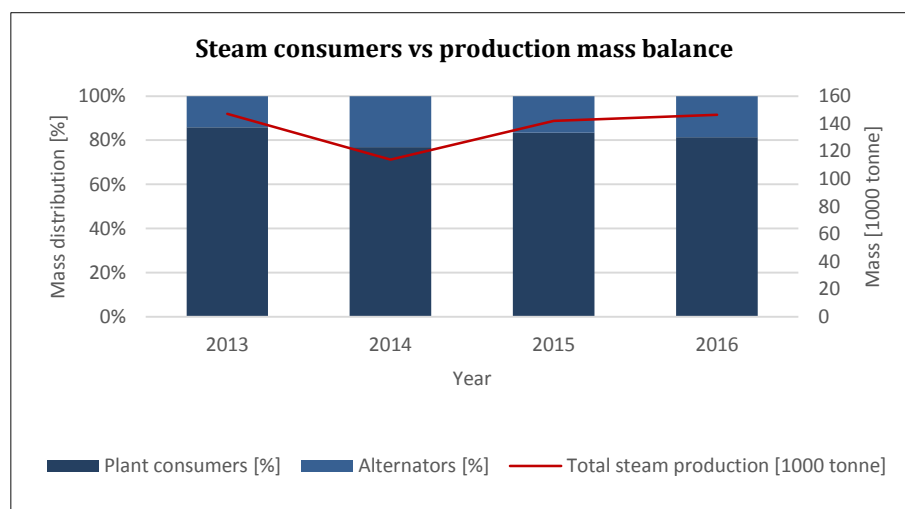


Figure 41: Case study steam network mass balance and average monthly mass production for 2013 to 2016

The steam consumption remained constant from 2013 to 2016 at 80% for the plant consumers and 20% for the alternators. However, in 2014 the ratio as well as the steam production differed. The steam production fell from 150 000 tonnes to 115 000 tonnes. This reduction was due to the blast furnace reline in 2014 which significantly reduced the BFG for the year. The steam production decrease in 2014 indicates that the steam production is dependent on BFG volumes.

4.2.7 Gas network management and distribution

The energy network is controlled from a control room within the energy distribution services department. An operator and assistant are responsible for a 12 hour shift. A day consists of two 12 hour shifts. The department cycles three shifts on a four-day basis. The operators control using a SCADA system while the assistant is responsible for visually inspecting the infrastructure on the plant.

Plants on the facility consume gas according to their demands. Each plant, therefore, can remove as much gas from the distribution network as required. This operation, however, is not safe without guidance from a holistic point of view. For example, if the plant should draw more COG from the system than supplied, then the COG holder would lose volume. If the holder should continue to lose volume, the water seal could damage the holder.

The operators at the energy distribution department's priority is to ensure a safe and balanced gas network. Only once the system is balanced and safe can the operators focus on optimal energy utilisation. A balanced network provides consistent gas for consumers. In the case of an unbalanced network, typically the gas type and quality change frequently. Operators would, therefore, sacrifice efficiency for a better-balanced network.

An indication of a balanced gas network is gas holders which remains at a constant level. If the gas holder level is dropping, then the by-product production is too little. This also applies when the holder level increases, the plants are consuming too little by-product gas. Gas is mixed if the COG gas holder is dropping too low which results in inconsistent gas for the consumers.

During normal operation, the operators of the energy distribution services make telephone calls to the different plants for a prognosis of their operation. The operators use this information to ensure that the network would remain balanced. Operators cannot automatically supply gas

around the works. Thus if required, the operators call the particular plants if they need them to change operation.

The energy balances done in Sections 4.2.3, 4.2.4 and 4.2.5 revealed that the mills are the largest consumer of natural gas and boilers of BFG. COG availability determines the amount of natural gas used in the mills. Ideally, the mills should only consume COG, and BFG should supply the boilers. However, if the mills are unable to consume COG, it is consumed by the boilers, thus resulting in a surplus of BFG being flared.

Additionally, from the other consumers, the facility drives the use of COG at the mills. This initiative has achieved the most significant natural gas reduction. COG is only used at the mills if there is a surplus available after the mills. It is more economical for the facility to save on natural gas than to generate electricity. That is, however, additional electricity generation from the emergency load.

As with most industrial facilities across the world, a SCADA is used to control the gas. Operators use the SCADA to monitor and control the plant. The system gathers and analyses data in real time. The software is efficient, user-friendly, customisable and reliable. The energy distribution section uses System 800XA from ABB [95]. The system's specialist at the section constructed a personalised GUI for the operators.

4.3 Implementation of controller on case study

4.3.1 System requirements

The case study complies with the infrastructural prerequisites. For the system to be adequate, the case study requires a by-product gas producer, a by-product gas distribution network and an on-site power generation plant. All of the requirements are met by the case study as depicted in Figure 42. The case study has coke ovens, a blast furnace and three BOFs which produce by-product gas.

From the three plant production by-product gas, the facility only reclaims COG and BFG. It was never deemed feasible to reclaim BOSG. The facility has a fully integrated gas distribution network. This network consists of gas holders and flare stacks and distributes natural gas, COG and BFG across the facility. The final requirement is met with the on-site power generation plant consisting of boilers and steam driven alternators.

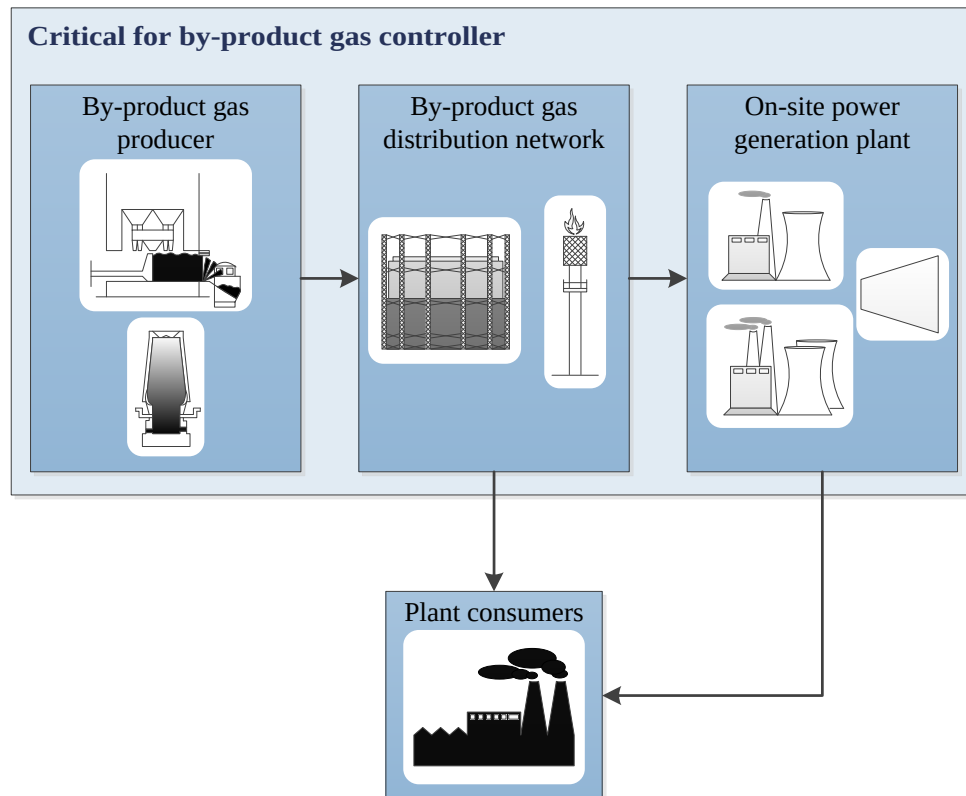


Figure 42: Case study system requirements

4.3.2 System analysis

The objective of the system analysis is to determine facility energy saving potential. Equation 1 defines the energy saving potential as the minimum among the by-product gases flared and the surplus capacity in steam and power generation. In this section, all three components are calculated to identify the minimum. Firstly, the amount of by-product gas flared will be calculated followed by the steam and electricity generation capacity.

COG and BFG are reclaimed and distributed across the facility as by-product gas. The system analysis includes both of these gases, their adjacent flare stacks, the four boilers and two alternators. The analysis is done with annual data from 2013 to 2016, and daily data for 2016. The purpose for analysing yearly data is to estimate any possible trends leading into 2017.

Equations 2, 3 and 6 are used to determine the by-product gas flaring, boilers and alternators additional capacity. A monthly averaged period is used comparing 2013 to 2016 and a daily period for 2016. The data were retrieved from a historian maintained by the controlling SCADA system. Monthly increments, however, do not reveal enough information regarding day to day operation. Therefore 2016 is analysed using daily data.

Figure 43 and Figure 44 illustrates the monthly average flaring for 2013 to 2016 and daily flaring for 2016 respectively. The COG and BFG flaring monthly averages reduced from 2013 to 2016. The reductions are due to the facility actively enforcing flaring reduction initiatives. A clear discrepancy is apparent in the amount of COG flared compared to BFG flared.

The discrepancy is partially due to reducing COG production in the relevant four years, and partly due to effective KPIs set for the operators. Management implemented these KPIs due to COG having a much higher energy per volume gas ratio. COG produced by the facility has 450% more energy per volume than the BFG.

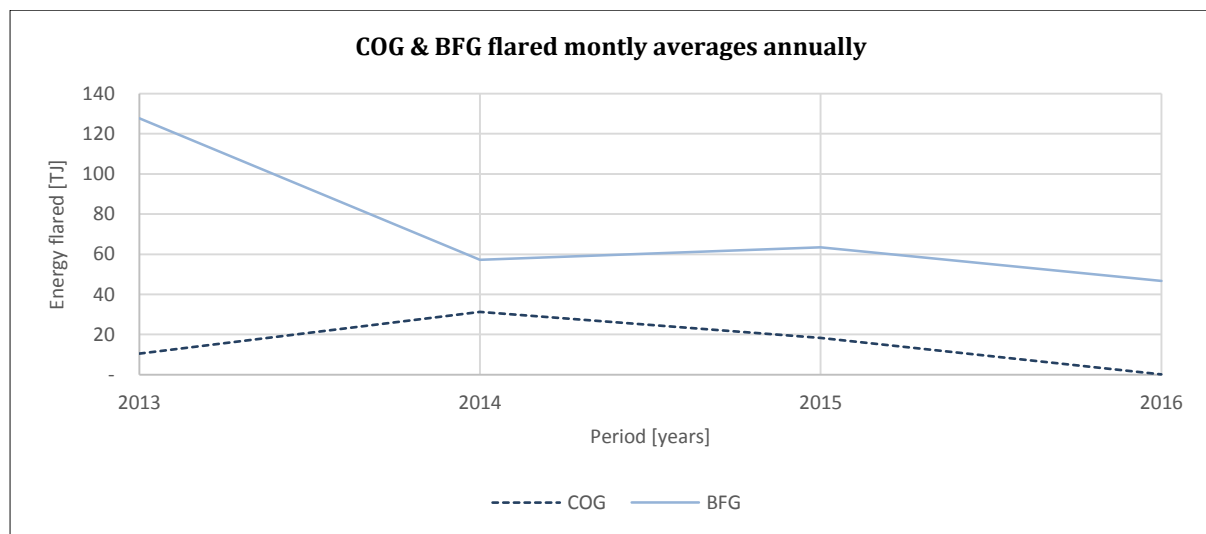


Figure 43: Case study average monthly COG and BFG flared for 2013 to 2016

The system analysis standardises units to energy (Joule). By comparison, 275% more energy is flared through BFG than COG. In 2016, 0.17 TJ and 46.76 TJ of COG and BFG were flared respectively. Thus, even though COG has more energy, the facility is losing more reusable energy by flaring BFG than COG.

The trends for COG flaring implies that in 2017 even less COG would be flared. However, according to the plant (Section 4.2.3), more coke ovens will be commissioned in 2017. More coke ovens in operation would result in more COG being produced. More COG available would possibly result in more COG being flared. Constant BFG production is projected for 2017.

Figure 44 illustrates that the daily flaring of BFG was generally around 1500 GJ per day. The flaring varied within a band of ± 1000 GJ. In the case of COG, most days had no flaring with

the exceptions of 20 GJ to 60 GJ. It is too difficult to accurately predict how the additional COG will influence the by-product gas condition. Thus, only data from 2016 is considered for the analysis regarding by-product gas flared.

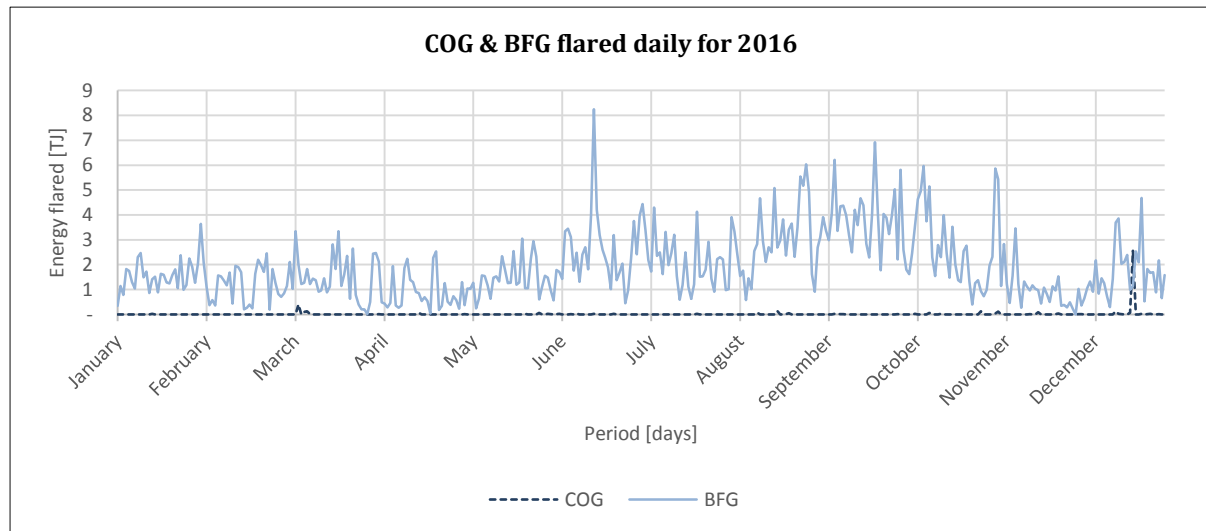


Figure 44: Case study COG and BFG flared daily in 2016

The following step is to determine the additional capacity at the boilers to generate steam. The on-site power generation plant has four boilers. These boilers have a maximum steam generation capacity of 400 tonne steam/h. The boilers' configuration consists of two small and two large boilers. The smaller boilers can generate 50 tonne steam/h, and the larger boilers can generate 150 tonne steam/h.

It is common practice for the facility to operate the on-site power generation plant without all the boilers operational. A boiler is frequently unavailable due to either repair, maintenance, or upgrades. The facility does, however, strive to always operate with at least a single small and large boiler simultaneously. Thus the steam generation capacity for the boilers will always be 200 tonne steam/h or more.

Figure 45 illustrates the monthly average steam generation of the boilers in TJ energy, thus energy required from the fuel gas to generate the steam. According to the facility, a constant boiler efficiency of 3.2 GJ per tonne of steam is achieved by the on-site power generation plant. This efficiency was used to determine the amount of energy required.

The actual amount of steam generated compared to the capacity of the boilers are compared in Figure 45. Each boiler configuration is shaded in a different colour. A constant amount of steam

has been generated monthly for the four years, just below 500 TJ. The facility projects the same amount of energy consumption in 2017.

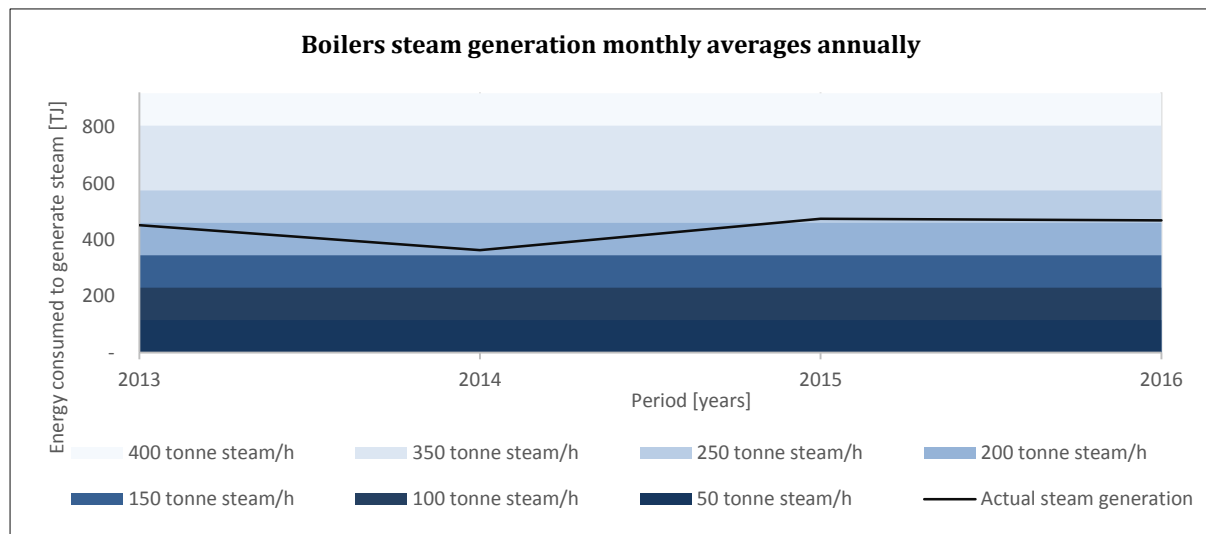


Figure 45: Case study average monthly energy consumed to generate steam and steam generation capacity of boilers for 2013 to 2016

The actual steam generation can be generated with the available capacity of 250 tonne steam/h or less. Figure 46 illustrates the daily steam generation compared with the boiler's capacity for 2016. The results are similar to that of what the boilers can achieve in the generation with a capacity of 250 tonne steam/h. The personnel at the boilers predicted that for the larger part of 2017, the boilers would run on maximum capacity alternator between 400 and 350 tonne steam/h.

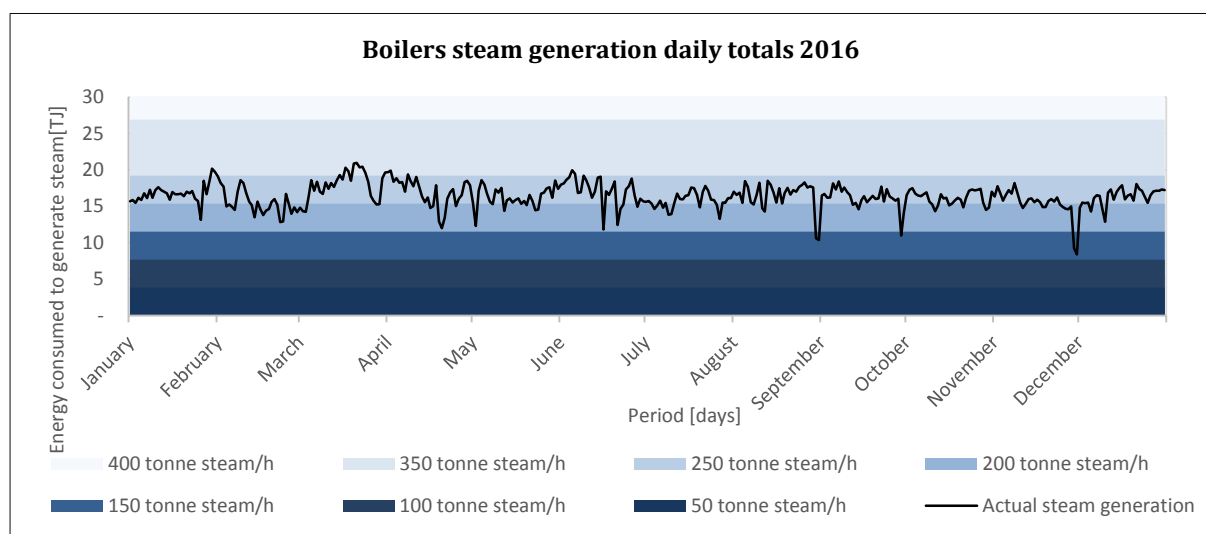


Figure 46: Case study daily energy consumed to generate steam and steam generation capacity of boilers for 2016

Assuming that in 2017 the boilers will have 350 tonne steam/h, the boilers will have a capacity to consume 26 TJ by-product gas daily. The average daily energy consumption of the boilers in 2016 was 15 TJ. Therefore, the additional energy consumption capacity of the boilers are projected for 2017 at 11 TJ per day.

The final part of the system analysis is the additional capacity for alternators. Figure 47 illustrates the monthly average electricity generation and the alternator's capacity for 2013 to 2016. Similar to the boilers, the electricity generation is standardised to GJ energy consumed to produce the actual generation. The facility has two identical alternators. These alternators were designed with a capacity of 10 MW each.

The actual generation capacity for the alternators are 9 MW each. However, if both alternators are operating, the maximum generation is only 16 MW. This is due to deteriorated condenser tubes constraining the alternators. Therefore, the capacity for single alternator operation was calculated at 9 MW and double alternator operation at 16 MW.

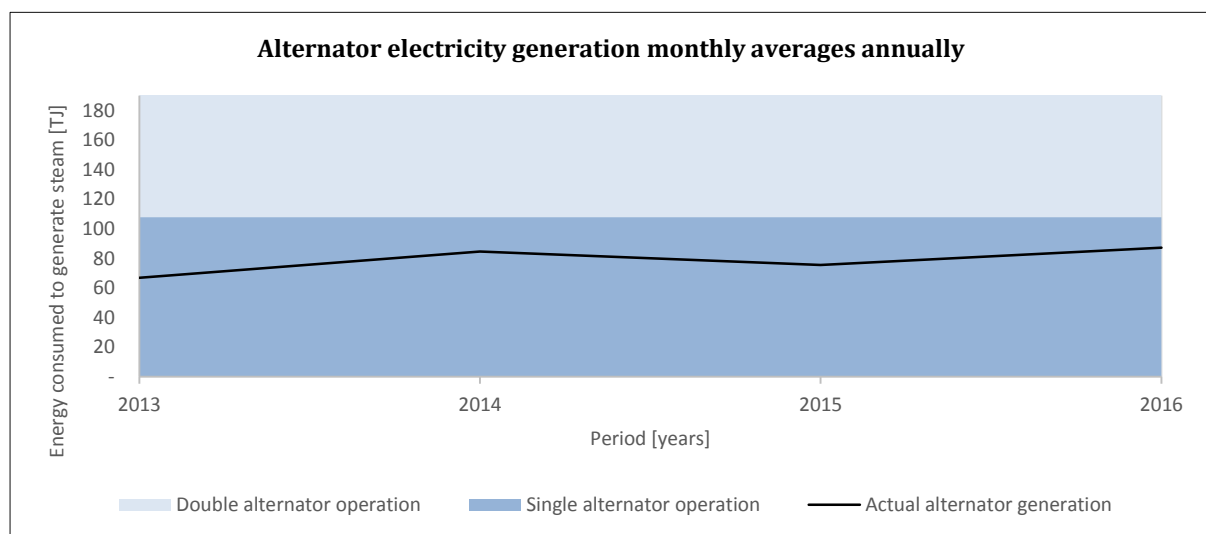


Figure 47: Case study average monthly energy consumed to generate electricity and generation capacity of alternators for 2013 to 2016

The alternators consumed energy consistently across 2013 to 2016. The monthly consumption remained just below 85 GJ. According to the facility, they project that in 2017 both alternators would be operational for the significant part of the year. The monthly generation for the particular years could be achieved with only one alternator operational.

Figure 48 illustrates the daily generation compared to the alternator's capacity for 2016. The daily data reveals similar results than annual monthly averages. For the most significant part

of 2016, only one alternator would have been enough. With the double alternator operational it allows for a daily energy consumption of 6 TJ. In 2016, an average of 3 TJ was generated daily. Therefore, the additional generation capacity for the alternators was calculated at 3 TJ.

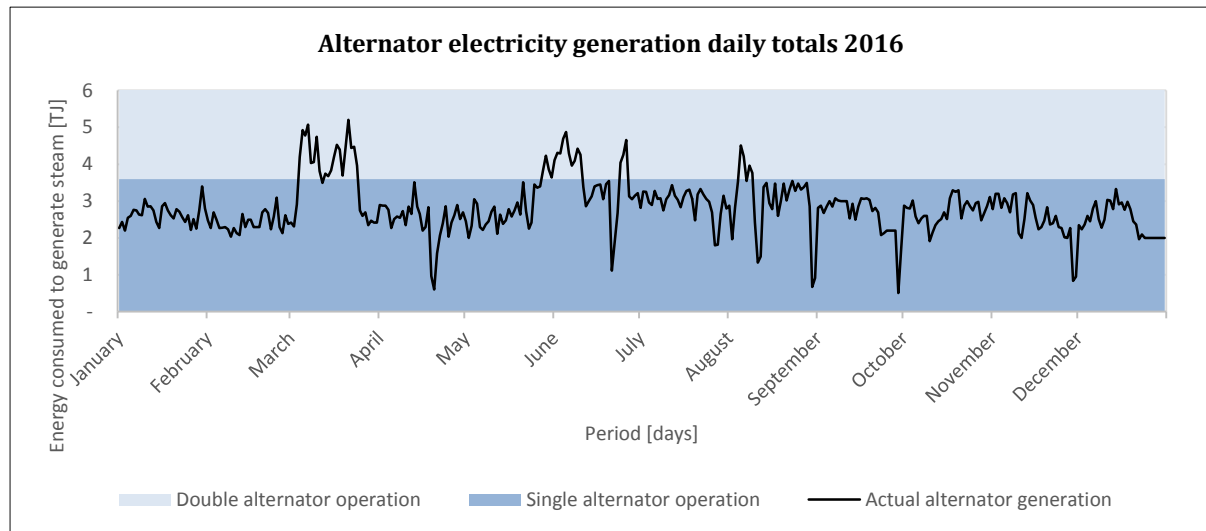


Figure 48: Case study daily energy consumed to generate electricity and generation capacity of alternators for 2016

In Table 6, the results of the system analysis is summarised. All three components including the by-product gas flaring, additional boiler and alternator capacity were calculated on a daily interval. The minimum among these was the by-product gas flared. According to the analysis, the boilers and alternators have sufficient capacity to use the 1.5 TJ flared on a daily basis. Therefore, the facility has a savings potential of 550 TJ for 2017.

Influencing factor	Daily
By-product gas flaring	1.5 TJ
Additional boiler capacity	11 TJ
Additional alternator capacity	3 TJ

Table 6: System analysis results summary

4.3.3 System constraints

Personnel confirmed the following system constraints:

By-product gas – The COG of the facility is constrained by the by-product gas on the case study and it is constrained by the COG. It is due to low COG production, poor cleaning of COG gas, and minimal flaring of COG. BFG, on the other hand, has plenty of scope due to high and

constant production rates as well as high volumes of energy being flared. Considering the condition of COG, the saving of the controller lies with BFG.

Distribution network – The gas distribution network interconnects the plant with gas supplied as a constraint due to plants having limited access to BFG. Most plants of the case study have access to COG, but only the boilers are considered as BFG’s largest consumer next to the blast furnace itself. Therefore, COG should ideally not be used in the boiler but rather for all the other consumers thereby reducing the requirement of natural gas.

Additionally, COG not being cleaned properly has led to additional maintenance to the distribution network and the plants itself. The naphthalene and tar form thick solids on the corrosion inside the pipes and the injectors get blocked. This has led to some plants rather wanting to use natural gas even when COG is available.

Gas holder – The gas holder’s only constraint is their high-high and low-low levels. It is critical that the gas holder may not operate above the high-high or below the low-low limit presented in Table 7. Failure to operate within these limits would potentially lead to a catastrophic failure of the gas holders.

Holder	Capacity [m ³]	High – high [%]	Low – low [%]
COG	15 000	15	75
BFG	80 000	10	80

Table 7: Case study COG and BFG holders’ capacity and operating limits

Flare stack – There are no constraints with the flare stacks. Each flare stack operates with a set point which is coupled to the gas holder level.

Boilers – The boilers are individually controlled for the boiler’s control room itself. It is not possible for the process controllers to operate the boilers from the gas distribution services. The other constraint is that the boilers can become unstable in instances where the amount of fuel gas and steam generation is adjusted too rapidly.

Alternators – The condition of the alternators is their only constraint. If proper maintenance is done, then the alternators can ramp up and down as desired. However, constant high production demands and the lack of proper maintenance of the alternators sometimes limits generation capacity. For example, conditions like sparking of the slip rings, dirty condenser tubes, etc. limit the generation.

4.3.4 Controller design

The system evaluation was used as a platform to design the by-product gas controller. Considering the system requirements, both the COG and BFG network has the required prerequisites for the controller. The system analysis, however, revealed that COG flaring has little room to be reduced. However, BFG has a significant amount of energy reduction scope. Therefore a controller is only designed for the BFG network.

It is redundant to control COG as there is no savings potential. The controller can, however, be updated at any time to include the COG network. The system constraints which the controller needs to consider include the ramp up and ramp down limitations of electricity generations as well as the gas holder limits. Additionally, the alternator should ideally generate in tiers of 0.5 MW intervals.

The controller was designed to control the alternator set point according to the parameters mentioned above. Operators also requested that if the BFG production reduces, that the control should automatically reduce generation. This was incorporated in the controller design by adding the cold blast air as a controlling factor. Through operation observations, the ideal cold blast air flowing to control accordingly were 2000 Sm³/h and 2500 Sm³/h.

Figure 49 illustrates the control philosophy. If the cold blast air volume is above 2500 Sm³/h, electricity generation is controlled according to the gas holder level. Different gas holder level ranges are allocated to different electricity generation set points. If the selected electricity generation set point does not fall between the upper and lower generation limit, it becomes the limit. This is repeated unless the cold blast volume is below 2500 Sm³/h.

In the case that the cold blast volume is below 2500 Sm³/h but above 2000 Sm³/h, the alternator set point is set at 5.5 MW. If the cold blast volume drops below 2000 Sm³/h, the alternator set point is further reduced to 5 MW. Only when the cold blast volume rises above 3000 Sm³/h, can the control resume on the gas holder levels. A cold blast volume of 3000 Sm³/h would ensure that the gas holder has gained enough gas after the low production rates.

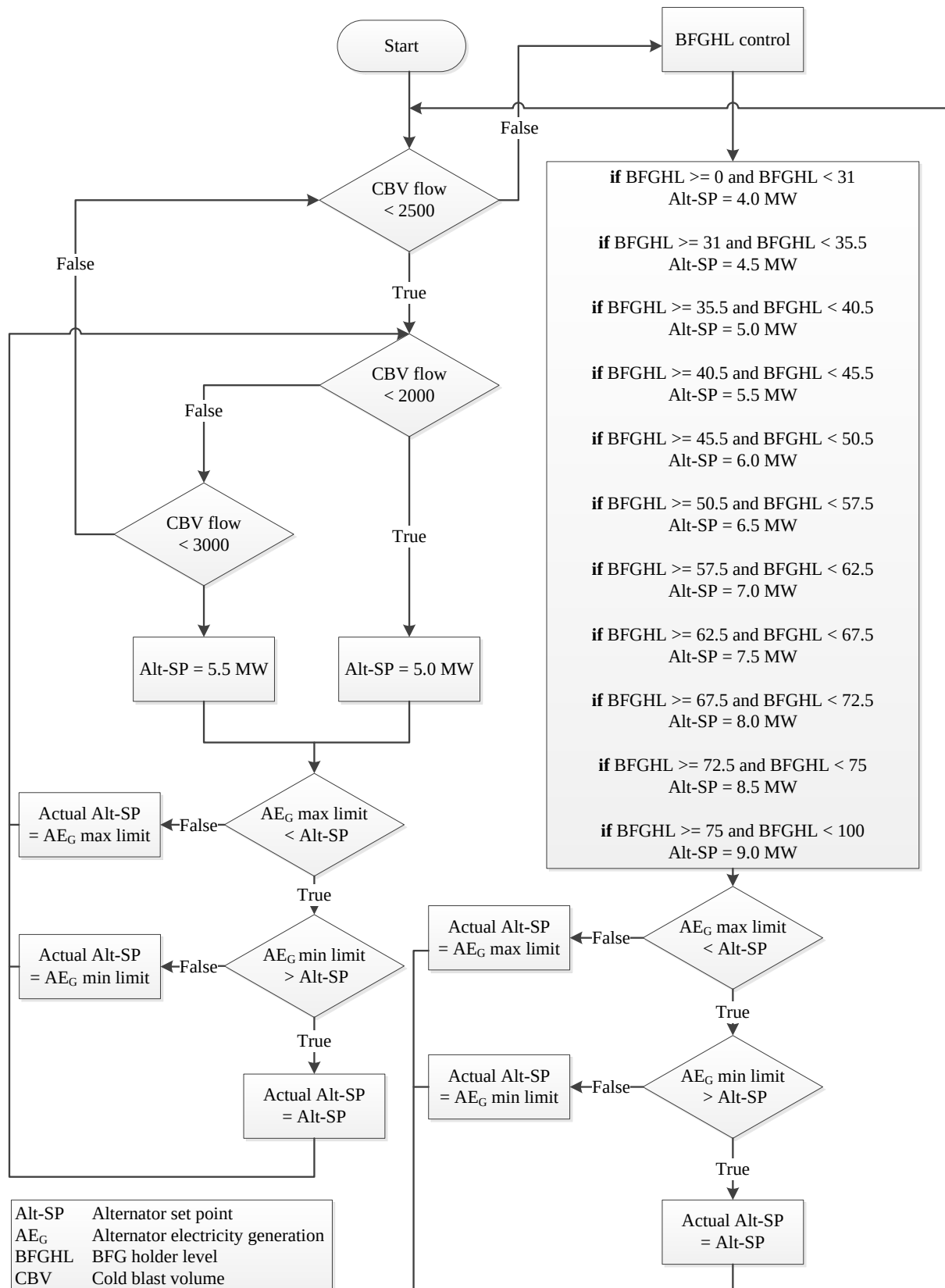


Figure 49: Case study by-product gas control philosophy

4.3.5 Simulation development

The simulation was developed to test and possibly refine the controller on the actual system, without the danger of damaging any infrastructure. Actual system characteristics were incorporated into the simulation. The simulation consisted of four different steps. These steps include importing relevant data, control, system balance and export data. In the first step, the initial values and system characteristics are imported.

The system characteristics are used to replicate the actual facility. The following step in the simulation is to control according to the inputs, which leads to the third step, balancing the system. An accurate balance of gas steam and electricity is key to a true simulation. It is critical that no energy is lost or gained wrongfully. Several tests were done to ensure that the electricity generation, steam generation and by-product gas volumes balance.

The final step of the simulation is to export the results. Results were exported as CSV files and graphs directly from Python. Numerous graphs were used during the simulation process. Three of these graphs proved sufficient to represent the actual impact. In these graphs, the simulated vs actual electricity generation, by-product gas flaring, gas holder levels as well as the accumulated flaring reduction and flaring reduction percentage are plotted.

Two simulated days are used to prove that the controller is suitable for actual control. On the first day, as presented in Figure 50, Figure 51 and Figure 52, a significant part of the maximum daily generation is reached. The simulated gas holder level drops below the actual gas holder level due to the increased amount of electricity generated. Then, the most BFG is saved when a sudden increase of BFG shoots the holder up to the flaring set point.

The same is for the day presented in Figure 53, Figure 54 and Figure 55. The constant fluctuations in the BFG availability cause the operator to control the alternator conservatively. In the case of the controller, any increase in the BFG availability is utilised by the alternators. Both the days presented are unique. On the first day an overabundance of BFG was available, and on the second day, the availability of BFG constantly fluctuated.

The facility granted permission to implement the control due to the simulation proving a safe optimised control. Additionally, the plant personnel valued the addition of such a simulation. The simulation allows them to test different control strategies without risk. It is essential to update the simulation each time the plant has undergone characteristic changes.

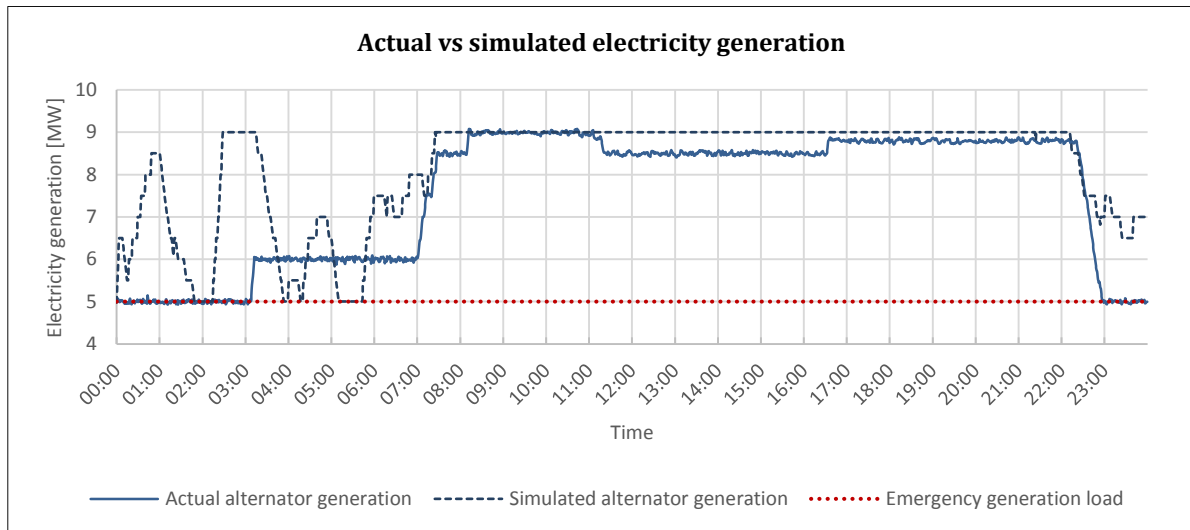


Figure 50: Case study simulation example day one generation

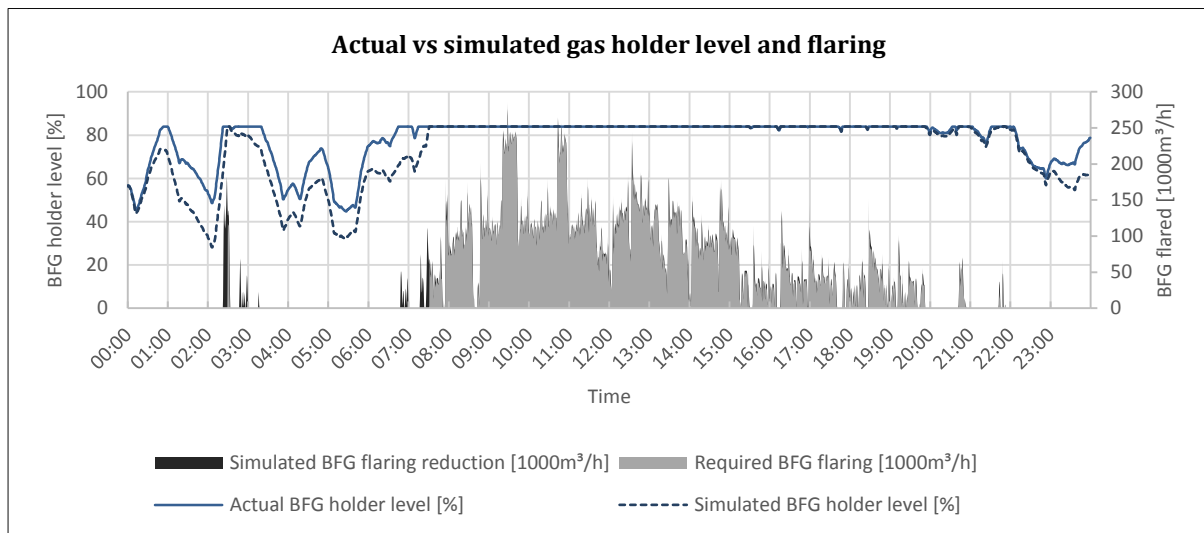


Figure 51: Case study simulation example day one flaring and gas holder levels

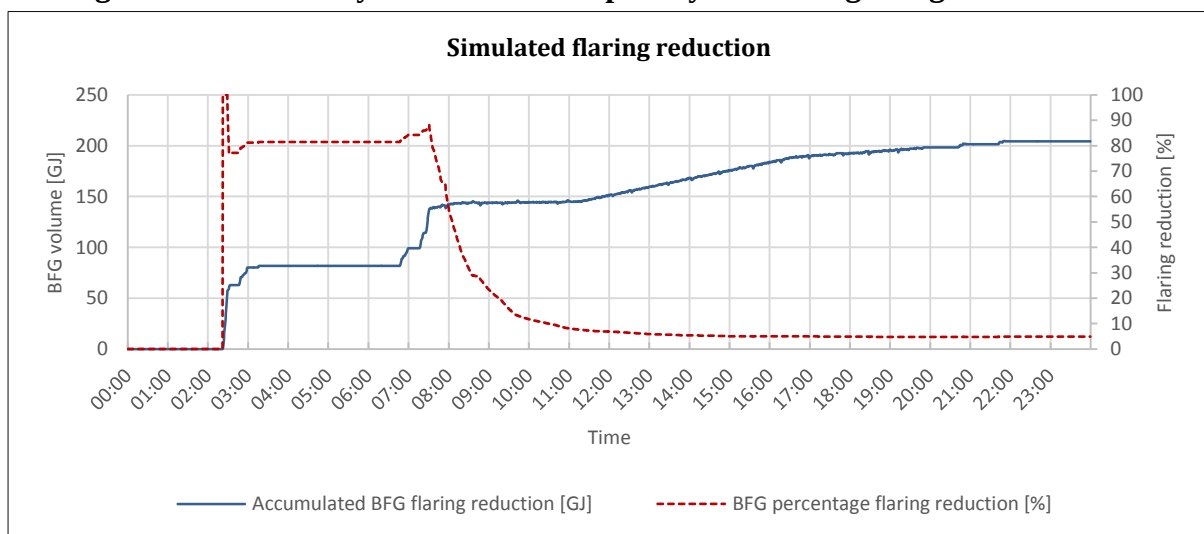


Figure 52: Case study simulation day one flaring reduction and cost savings

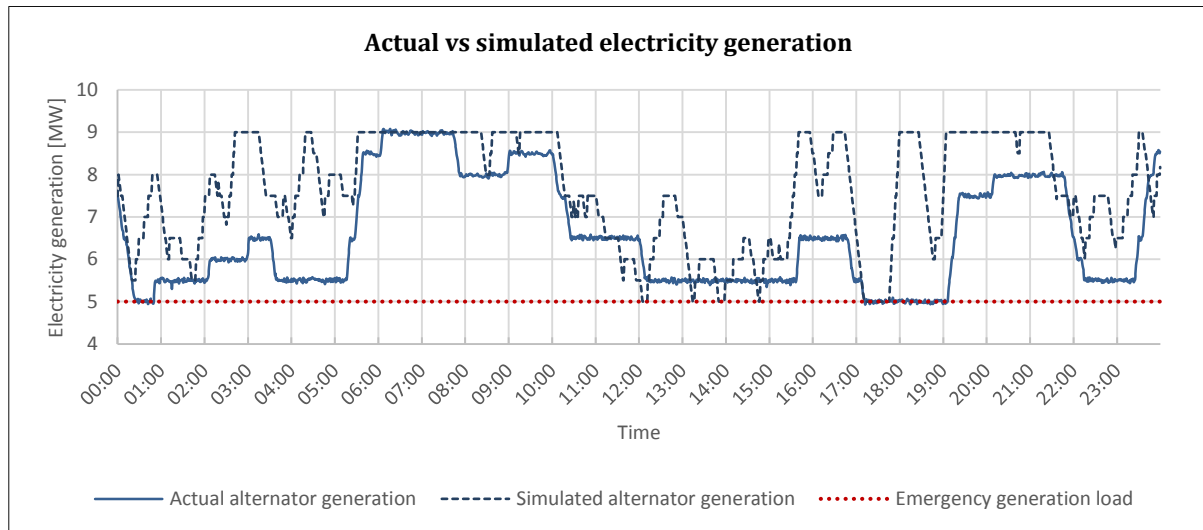


Figure 53: Case study simulation example day two generation

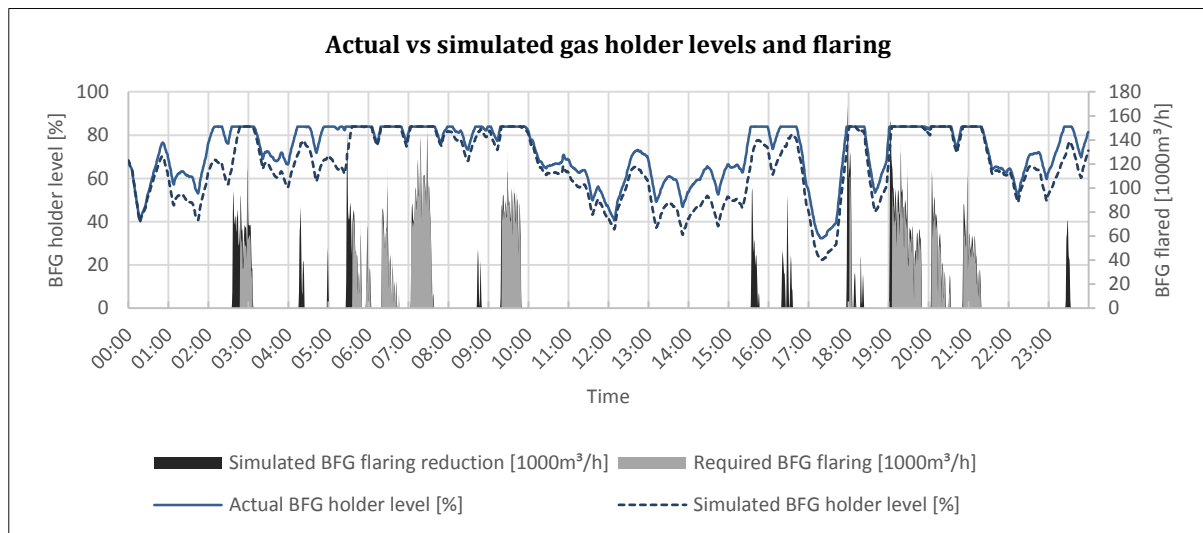


Figure 54: Case study simulation example day two flaring and gas holder levels

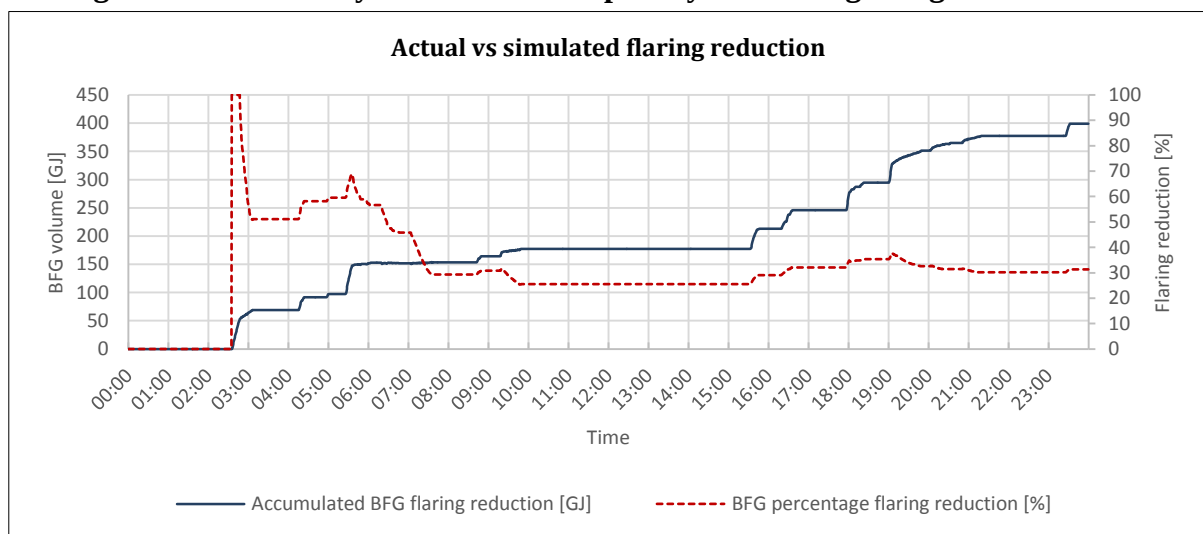


Figure 55: Case study simulation day two flaring reduction and cost savings

4.3.6 Controller implementation

Permission was granted for the case study to implement the controller directly into the SCADA system. The 800PX control from ABB, used by the plant, has the ability to code a personalised control. The control philosophy was structured in a function block format. With guidance from the systems, specialist control was incorporated into the SCADA according to the function block structure.

An auto control active button, as well as maximum and minimum limits were added to the GUI. These functions allow for the operators to enable, disable and assign limits to the controller. It was important to give the operator the ability to enable or disable the controller. It allows them to remain in control and responsible for the system. It is the same with the electricity generation limits. These limits allow for safe operation if the system is constrained.

It is important that the operators report when using these limits. Operators may start controlling according to the limits rendering the control redundant. The reasons why the operators use the limits should be addressed. Ideally, the control should be on auto and no limits used.

Additionally, the study revealed that during implementation, operators started to reject the idea of the controller. The reason for the opposing behaviour was operators feeling that their contribution is less significant, thus threatening their job security. It is important to ensure that the control is there to aid rather than replace. Only once this mind-set is achieved, will operators actively use the controller.

4.3.7 Boundaries of the baseline models

Figure 56 illustrated the control dependants and baseline model boundaries. The controller uses the cold blast air volume of the blast furnace and the BFG holder level as to control the alternators generation. Thus the blast furnace, BFG gas holder, and both the alternators are controlling dependents.

The baseline boundaries should include only the involved mechanisms. These have been identified as the BFG gas holder, BFG flare stack, the four boilers and the two alternators. The controller can only affect these sections. The same baseline boundaries apply to each baseline model presented in this study. If the control is extended to the COG network, then the boundaries will also include the COG holder and flare stack.

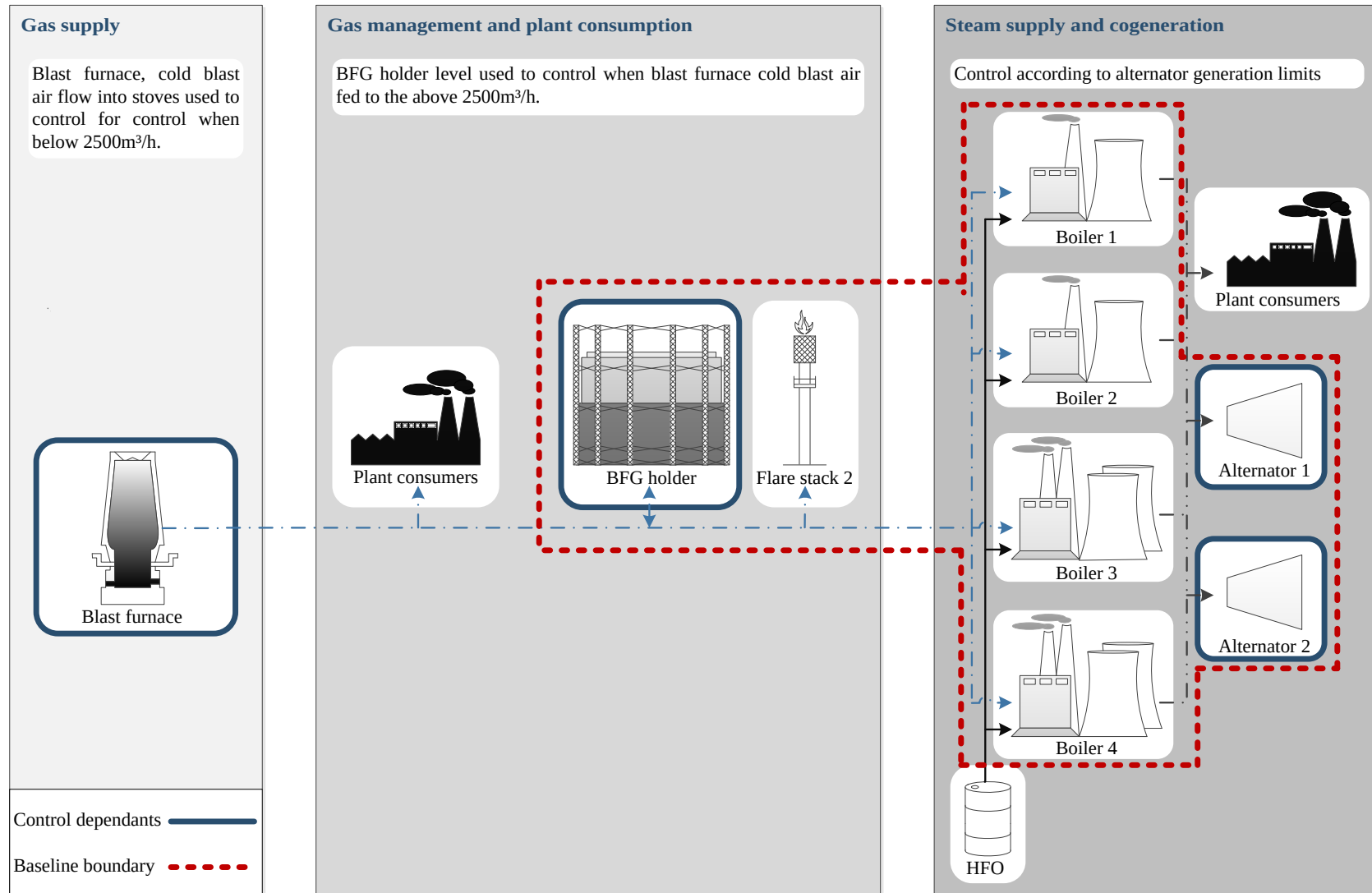


Figure 56: Case study control dependants and baseline models boundaries

4.3.8 Metering period

The metering period should represent typical operation without the control. However, the system characteristics change frequently. Thus, the longest period of which the data remained relatively constant before implementation is used. This period was 30 days prior to implementation. During this period only one of the two alternators were running. Figure 57 illustrates the alternator generation prior to control implementation.

The control was implemented on the 330th day on Figure 57. The alternators had difficulties the month before implementation with maximum generation. This limitation, however, is more prominent in the second month before implementation. The facility agrees that no major changes were done on the alternator within the month before implementation.

The difficulties of generation between the third and fourth month before implementation was due to the boilers losing an Induced Draft (ID) fan. Steam generation without this fan forced minimum use of BFG at the boilers. Thus, the alternators were limited due to low steam production from the boilers. In the preceding months, maximum generation was generally between 7 and 8 MW due to maintenance requirements on the alternators side.

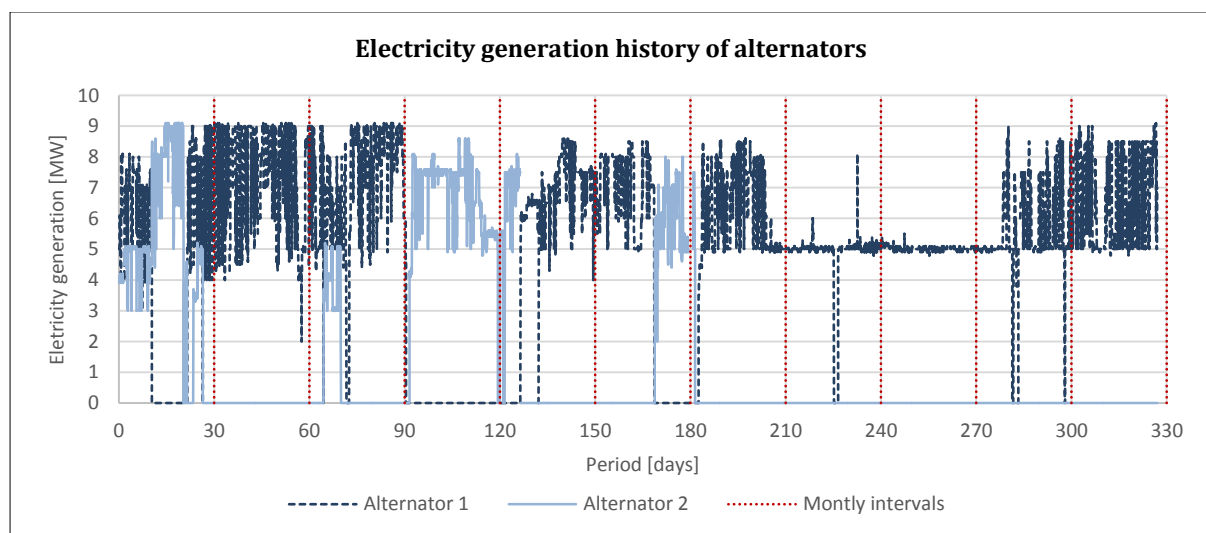


Figure 57: Generation by 330 days prior implementation of controller

It is crucial to select relevant representative data when developing a baseline. Changes to the gas system, boilers and alternators prevent the use of data too far in the past. Relevant plant personnel, therefore, agreed that the baseline period should be the month before the controller was implemented.

4.3.9 Routine adjustments

Baseline model 1

Baseline model 1 consists of a constant routine adjustment model. The routine adjustment is calculated as the average BFG flared per day across the baseline period. Figure 58 illustrates the daily flaring compared to the average flaring for the month before implementation. Four days were declared as condonable. The constant flaring used for the routine adjustment was calculated at just below 2000 GJ. Thus the routine adjustment for baseline model 1 is 2000 GJ.

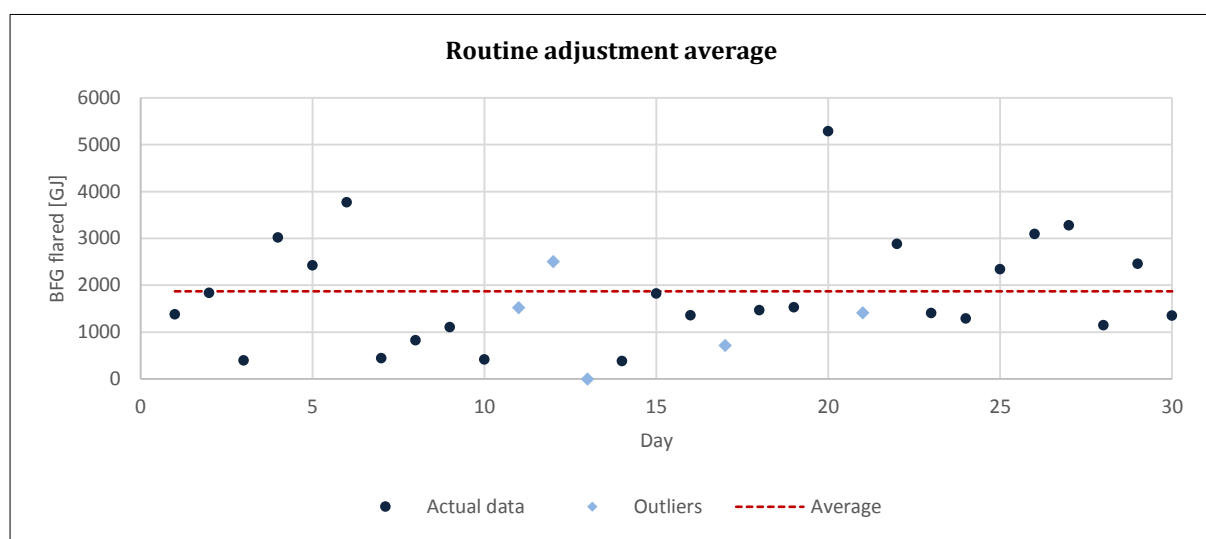


Figure 58: Case study Baseline model 1 routine adjustment

Baseline model 2

Baseline model 2 consists of a constant factor routine adjustment. This constant factor is the percentage BFG flaring reduction benefit of the controller. The constant factor was calculated using the simulation. The actual daily BFG flaring was compared to the simulated and average flaring. The average reduction percentage was calculated at 21%.

Figure 59 illustrates actual flaring and electricity generation compared to the simulated flaring and electricity generation. The BFG not flared in the simulation is used to generate electricity with the alternators. Thus, the simulated BFG flaring is less but electricity generation more.

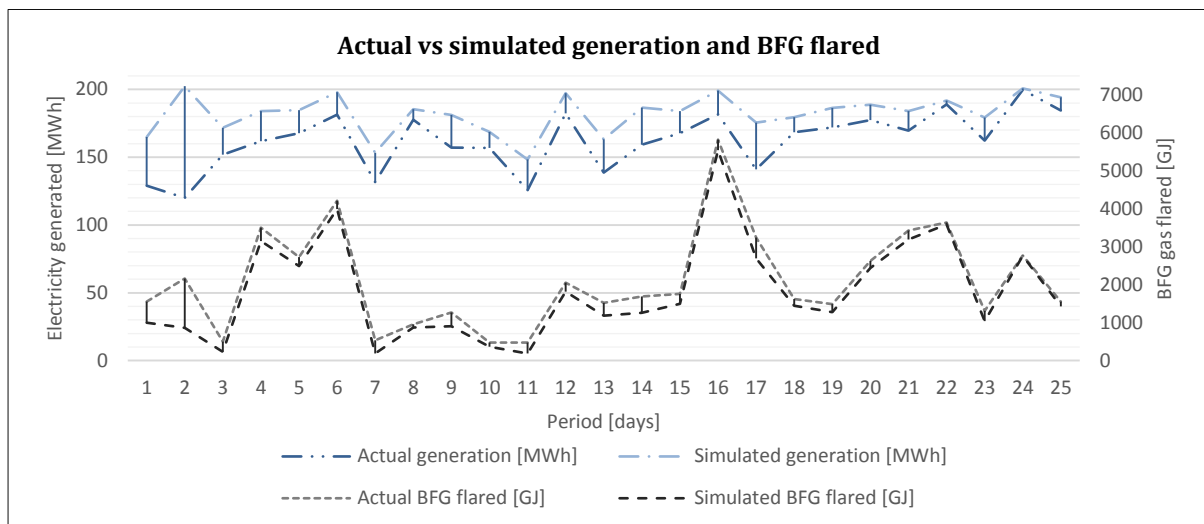


Figure 59: Case study baseline period actual and simulated generation and BFG flaring

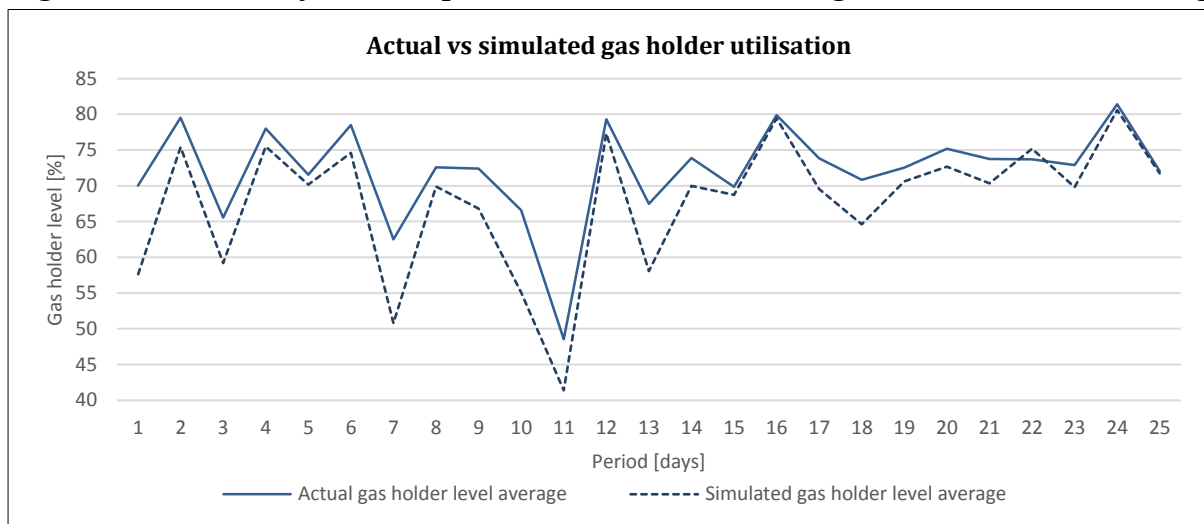


Figure 60: Case study baseline period actual and simulated gas holder level

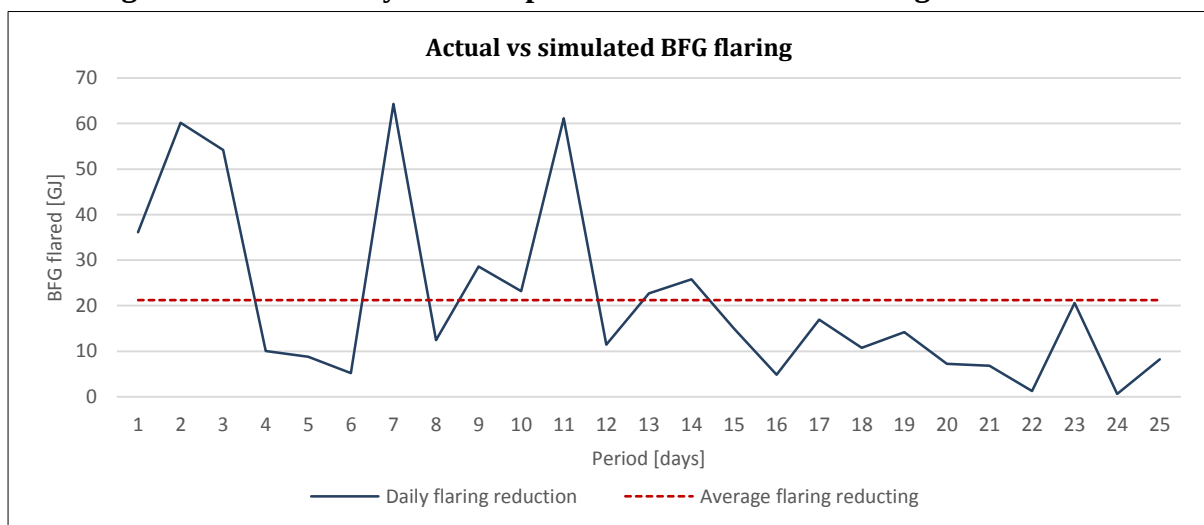


Figure 61: Case study baseline period simulated flaring reduction percentage

Figure 60 illustrates the actual vs simulated average daily BFG gas holder levels. Figure 61 illustrates the calculated flaring reduction percentage for the baseline period. As expected, the simulation utilises the BFG more efficiently thereby keeping the gas holder level, on average, lower than what actually happened.

According to the simulation, the days where the highest flaring reduction was achieved were the days the actual flaring was moderate. This indicates that the controller has the highest influences on days where surplus BFG is moderately available. The controller does not have much of an impact for too much or little BFG available. The constant adjustment factor for Baseline model 2 is 21%.

Baseline model 3

Baseline model 3 is similar to Baseline model 2, however, in Baseline model 3, a regression model is used. The regression model determines the flaring reduction constant. Adding the regression model compensates for Baseline model 2 not including the electricity generation capacity. The regression model was constructed with the simulated data. Figure 62 illustrates the regression model between the simulated flaring reduction and electricity generation.

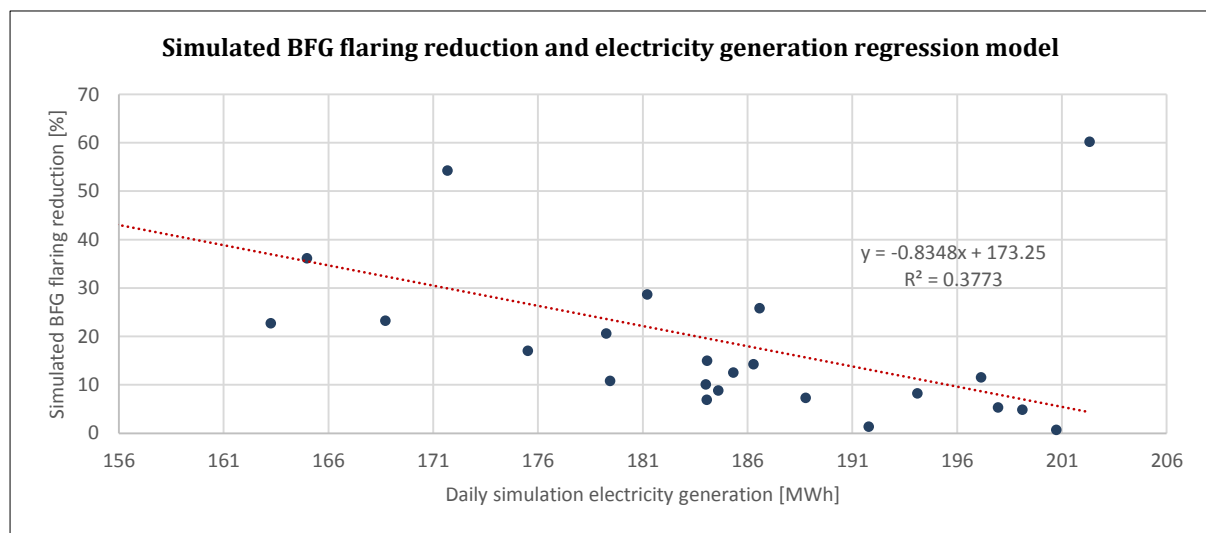


Figure 62: Case study Baseline model 3 flaring reduction to generation regression model

The regression model does not have a good fit with a R-squared of 0.3773. In the case of a good fit, the R-squared should be as close to one as possible. There is, however, a visual correlation. Typically, a poor fit like the one presented will not be used. It is important to

consider that the model is dependent on human operation. It is the human operation which is responsible for the poor curve fit.

The regression model does have the expected gradient. This gradient indicates as the flaring reduction potential decreases, the electricity generation increases. Considering the curve gradient and that this is not the only baseline model, the regression model will be used. Thus, the flaring reduction constant for Baseline model 3 is calculated by substituting the actual electricity generation as x into $y = -0.8348x + 173.25$.

Baseline model 4

The routine adjustment factor for Baseline model 4 is calculated with a regression model. Baseline model 4 determines the electricity generation rather than BFG flaring. The regression model is between the electricity generation and sum of BFG flared and sent to the boilers. Figure 63 and Figure 64 are two regression models representing daily and half hourly intervals.

The regression model for the daily intervals has a much larger R-squared than the half hourly intervals. It is important to note, similar to Baseline model 3, this type of regression fitting would typically be unacceptable. However, the measurement complexities caused by the human factor and the amount of baselines models used in this study justify using these models. Therefore the routine adjustment for Baseline model 4 is calculated by substituting the actual daily sum of BFG flared and sent to the boilers as x into $y = 0.005x + 106.6$.

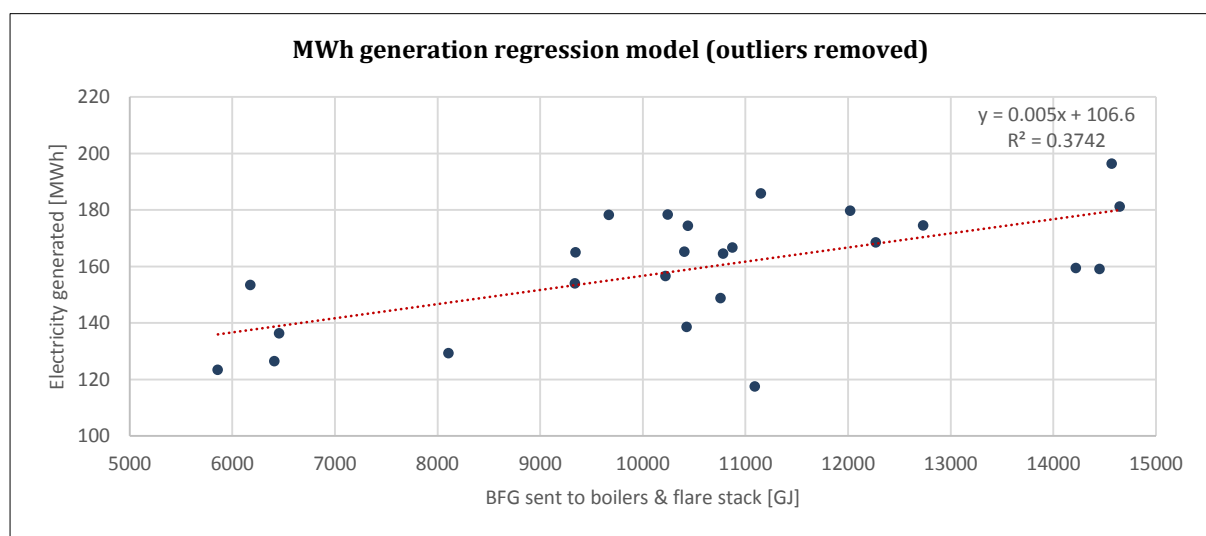


Figure 63: Case study Baseline model 4 generation to BFG flared and sent to boilers daily regression model

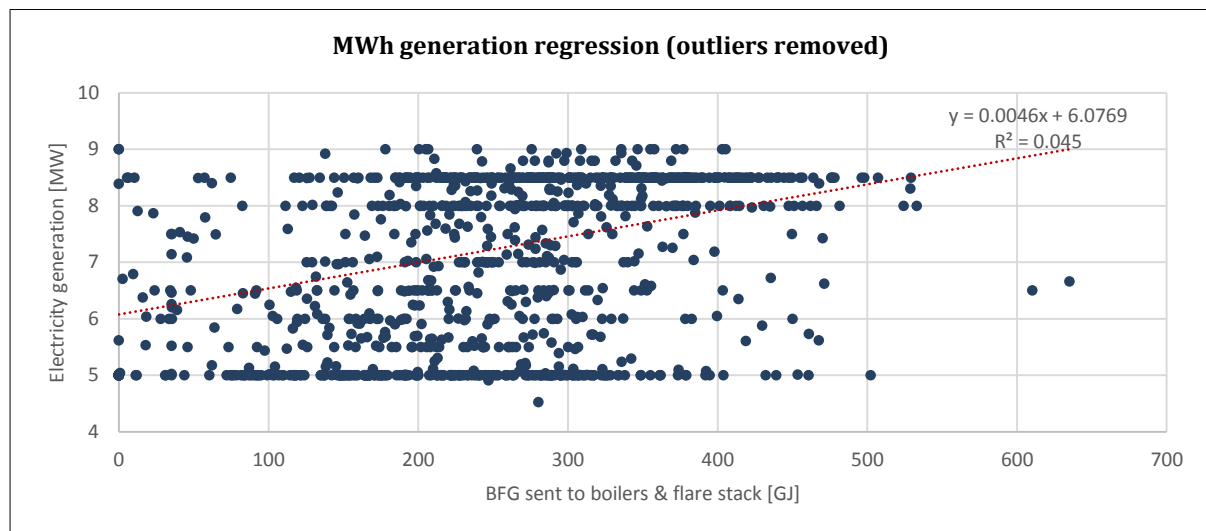


Figure 64: Case study Baseline model 4 generation to BFG flared and sent to boilers half hourly regression model

Baseline model 5

Baseline model 5 is different to the other baseline models because the baseline period is before and after the controller was implemented. The model uses a constant electricity generation factor to calculate the routine adjustment. Figure 65 illustrates the electricity generation during the baseline period. From day 1 to 30 was before implementation. The controller was implemented from day 31 to 38. From day 39 to 68 the controller was used by the operators. Day 31 to 38 is excluded from the baseline.

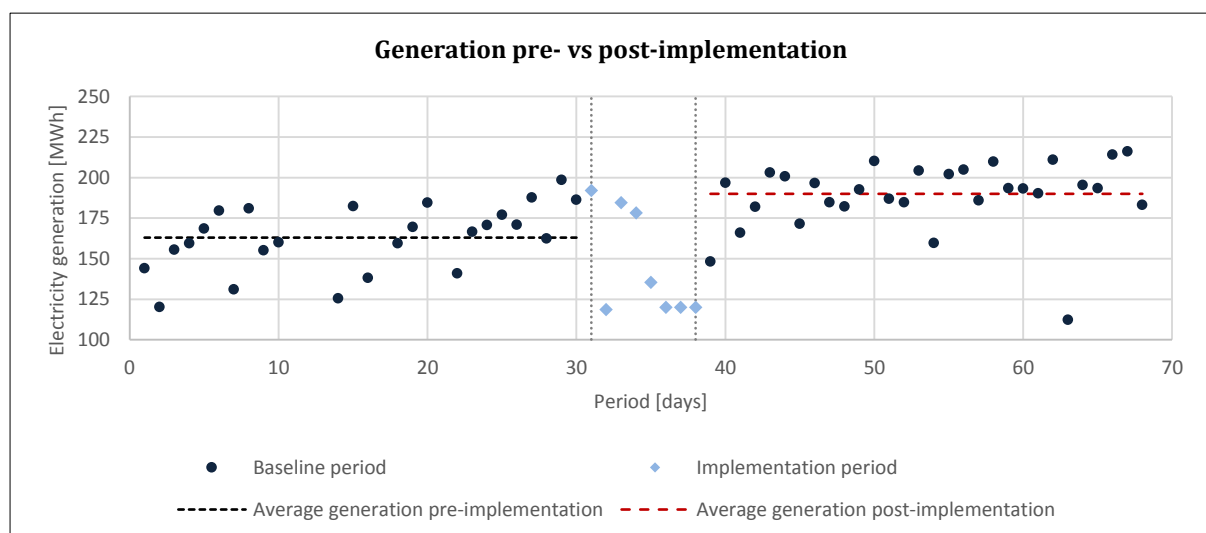


Figure 65: Case study Baseline model 5 generation pre- vs post-implementation

The constant generation factor was calculated with the average daily generation before and after the controller was implemented. A controller benefit of 14.6% was calculated. Thus the routine adjustment for Baseline model 5 is calculated as 14.6% of the actual daily electricity generation.

4.3.10 Saving quantification

The savings needs to be evaluated in monetary units. After the routine adjustment is determined (see Section 4.4), the amount of electricity saved is calculated. The electricity tariff used to calculate this value consists of three components. The first component is the TOU tariffs. A weight TOU tariff is used as explained in Section 3.5.6. Equations 23, 24 and 25 are derived from Equation 21. These equations represent the weekday, Saturday and Sunday weighted electricity tariffs used.

$$WET_{weekday} = \left[\left(\frac{5}{24} \right) * ET_{peak} \right] + \left[\left(\frac{11}{24} \right) * ET_{standard} \right] + \left[\left(\frac{8}{24} \right) * ET_{off-peak} \right] \quad (23)$$

$$WET_{Saturday} = \left[\left(\frac{7}{24} \right) * ET_{standard} \right] + \left[\left(\frac{17}{24} \right) * ET_{off-peak} \right] \quad (24)$$

$$WET_{Sunday} = \left[\left(\frac{24}{24} \right) * ET_{off-peak} \right] \quad (25)$$

The other two components remain constant. These components are the affordability subsidy, electrification and rural subsidy charge. The monetary saving is calculated by multiplying the electricity rate with the amount of electricity generated due to the controller. Both the day of week and the season are functions of the electricity rate.

4.3.11 Non-routine adjustments

No non-routine adjustments were made to the system during the two months post-implementation. The facility personnel mentioned a possibility of an additional alternator. This alternator would add generation during downtime. If an additional alternator is realised, it is considered as a non-routine adjustment. In this case, all of the baseline models need to be changed accordingly.

4.4 Performance assessment

4.4.1 Controller performance assessment procedure

This section is based on the controller's performance across two active months. The routine adjustments of each baseline model are compared with the actual data. Additionally, the fraction of the day that the controller actively controlled is also used in the evaluations. Operators confirmed that the control was not on manual during the period. The operators did, however, use the limits to constrain the controller.

The fraction percentage which indicates whether the controller controlled actively is an indication of active gas holder control. Low cold blast air volume does not reflect in these calculations. The reason for this was to determine the influence of active gas holder control. The benefit of the controller is only due to active gas holder control. It is rather a combination of awareness and automated control to aid the operator. Days where the baseline models show negative savings are regarded as days that there were no energy saving scope.

4.4.2 Baseline model 1

Figure 66 illustrates the performance of Baseline model 1. The benefit is the routine adjustment minus the actual BFG flared. It is clear that a constant baseline model cannot quantify the actual controller benefit. The calculated savings is irregular due to the noise in the system. The model reflects that the controller had little influence up to day 42 but a significant influence onward.

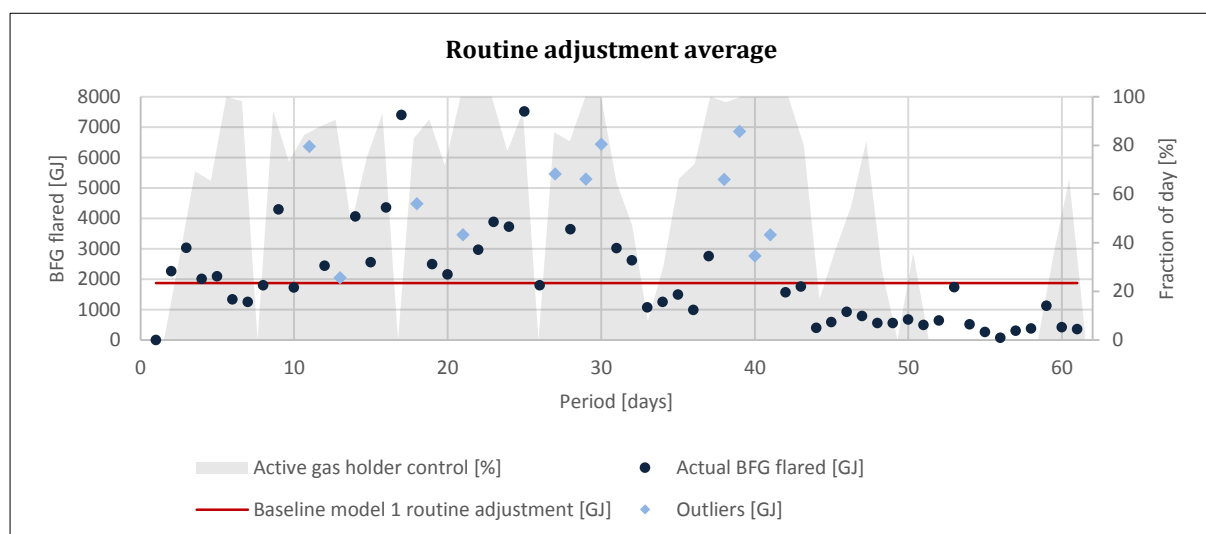


Figure 66: Case study Baseline model 1 routine adjustment and actual

The outliers were removed as condonable days. These days were agreed upon by relevant parties and removed to the generation or gas product constraints. The difference between before and after the 42nd day is by-product gas availability. The availability of by-product gas was less after the 42nd day resulting in less energy flared. A constant baseline cannot compensate for noise like gas availability and demand. Thus, due to the lack of this ability, a constant baseline is not suitable for the case study.

4.4.3 Baseline mode 2

Figure 67 illustrated the performance of Baseline model 2. The difference between the routine adjustment and the actual BFG flared is the benefit. The same outliers as in Baseline model 1 were removed as condonable days. The outliers were neutralised by making the routine adjustment the same as the actual BFG flared. This is due to the model not being able to compensate for electricity generation restrictions (see Section 3.5.5 under Baseline model 2). Apart from the outliers, the baseline model seems to represent the controller influence accurately.

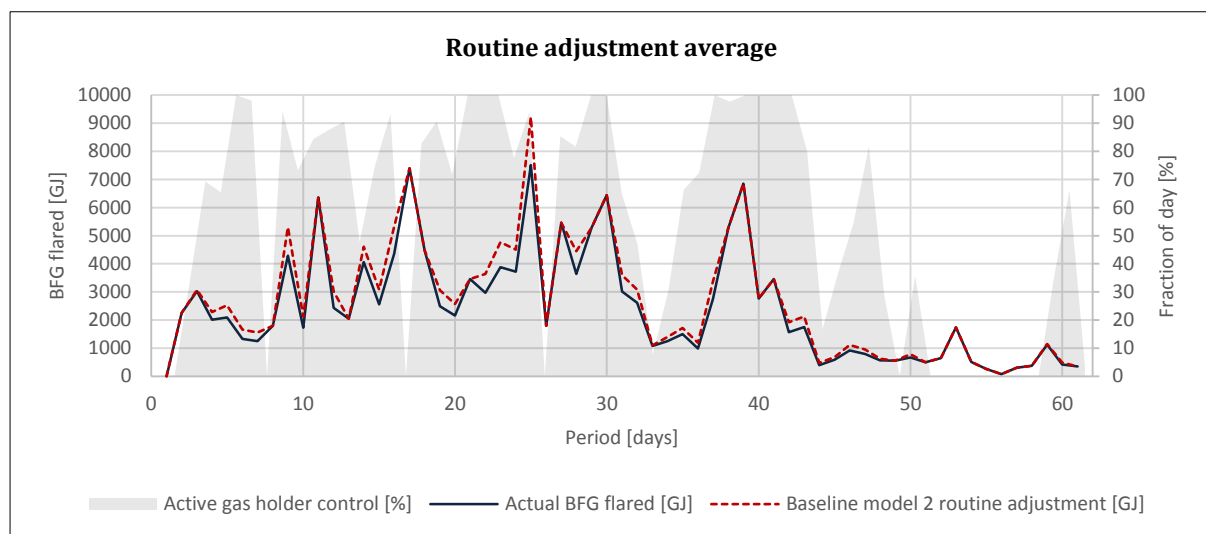


Figure 67: Case study Baseline model 2 routine adjustment and actual

The model reflects that for instances of high and low by-product gas availability, the controller did not have much effect. The 25th is, however, the exception. On this day significant volumes of by-product gas were flared indicating high savings. It might, however, be a condonable day that was missed. The flaw of Baseline model 2 is difficulties in identifying all the condonable conditions. The controller benefit can be related to active gas holder control. For the instances where the gas holder control was significantly active, the controller benefit was general higher.

4.4.4 Baseline model 3

Baseline model 3 did not include any condonable days. The model compensates for routine adjustments with the regression model. Figure 68 illustrates the performance of the baseline model. The model performed as expected, indicating that the controller benefit is the highest when moderate BFG is available. This is exactly the conditions where the control can benefit the most. Similar to Baseline model 2, a correlation can be made between active gas holder control and energy saved.

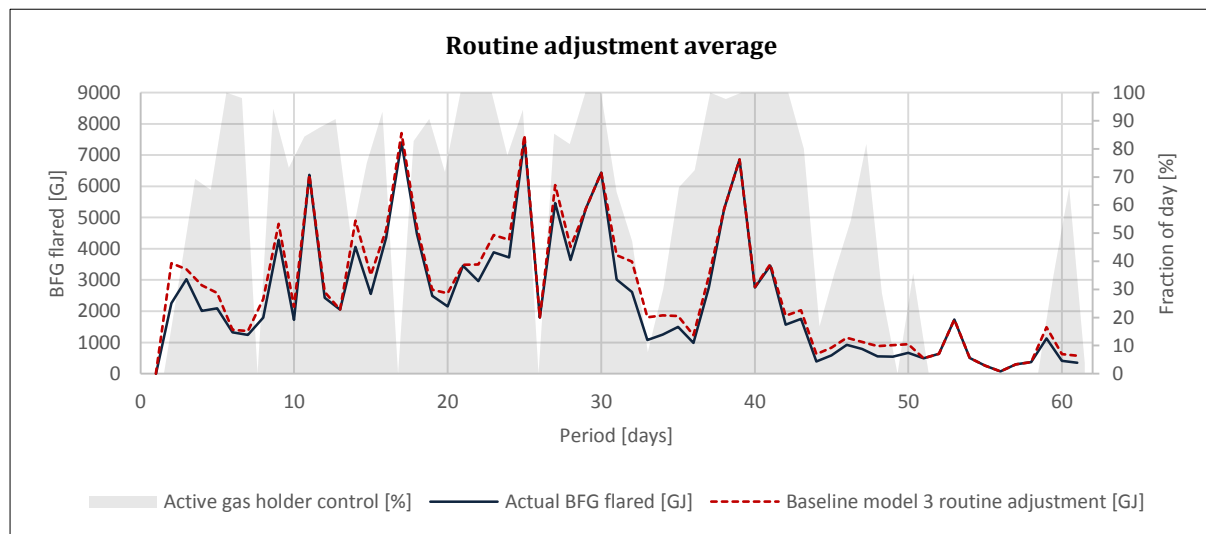


Figure 68: Case study Baseline model 3 routine adjustment and actual

4.4.5 Baseline model 4

Figure 69 illustrates the performance of Baseline model 4. The same outliers from Baseline model 1 and Baseline model 2 are considered as condonable days. Energy savings is the difference between the actual generation and the routine adjustment. The electricity generation increased after the controller was implemented. No correlation can be made between active gas holder control and the additional electricity generation.

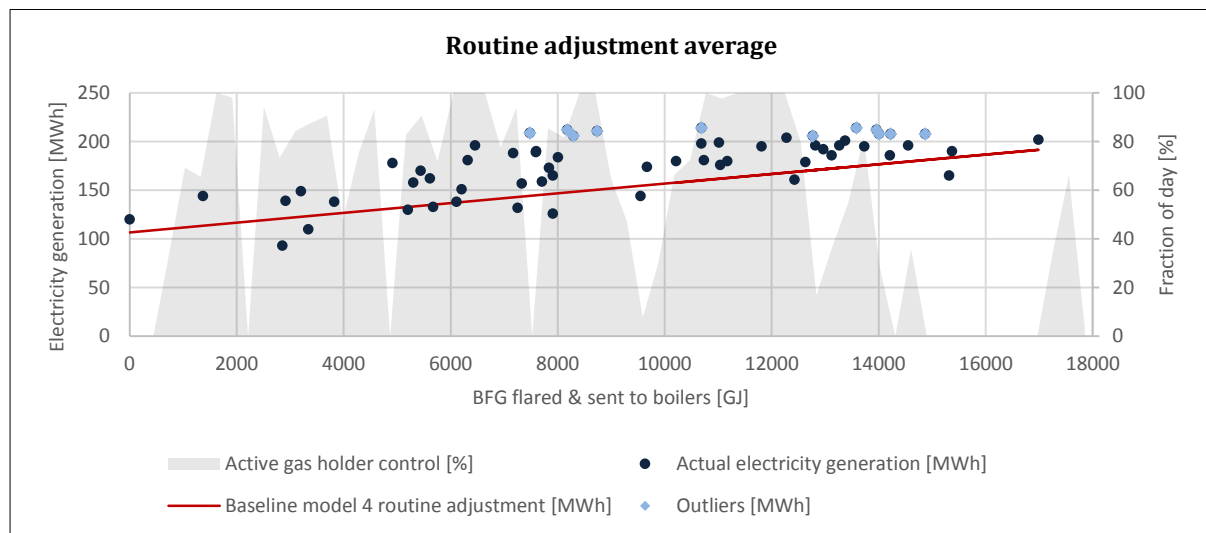


Figure 69: Case study Baseline model 4 routine adjustment and actual

4.4.6 Baseline model 5

Figure 70 illustrates the performance of Baseline model 5. The same condonable days from Baseline model 1 were used. If the day is condonable, the routine adjustment is made the same as the actual. Therefore a condonable day does not reflect any savings. The baseline model reports the most accurate benefit because it is constructed from data before and after controller implementation. The model does reflect a constant energy saving benefit. This benefit remains the same on the days that the control was significantly active and for days it was not.

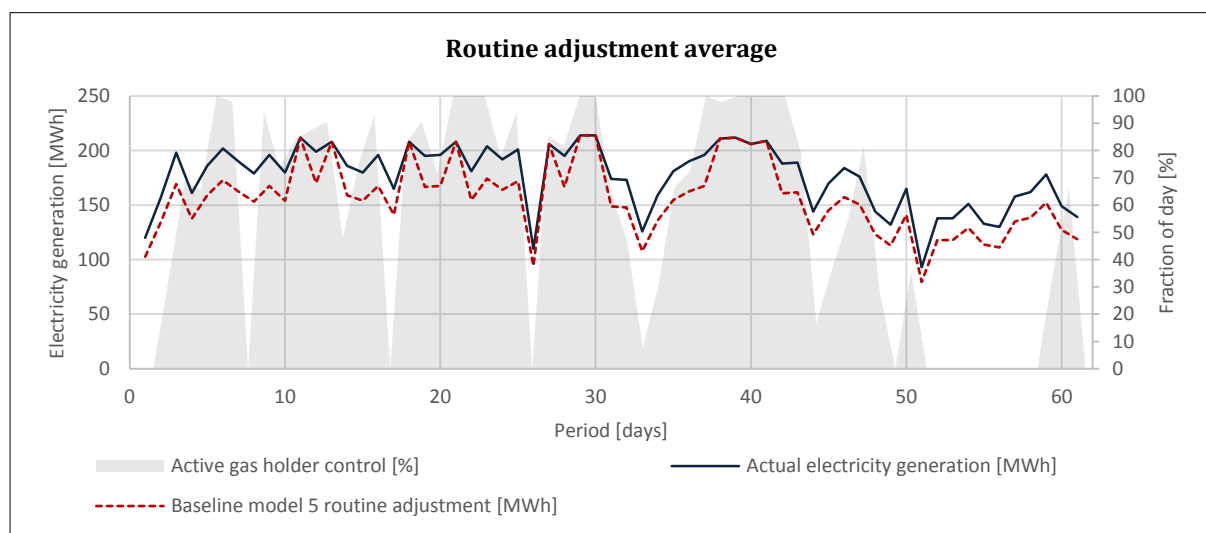


Figure 70: Case study Baseline model 5 routine adjustment and actual

4.4.7 Overall performance assessment

It is difficult to evaluate the performance of the different baseline models individually. The performance of the baseline models is compared with each other in Figure 71. The comparison is done in monetary values. Baseline model 1 achieved the highest savings at R1.6 million. Baseline model 2 to 5 fell within a band of R1 million to R0.6 million.

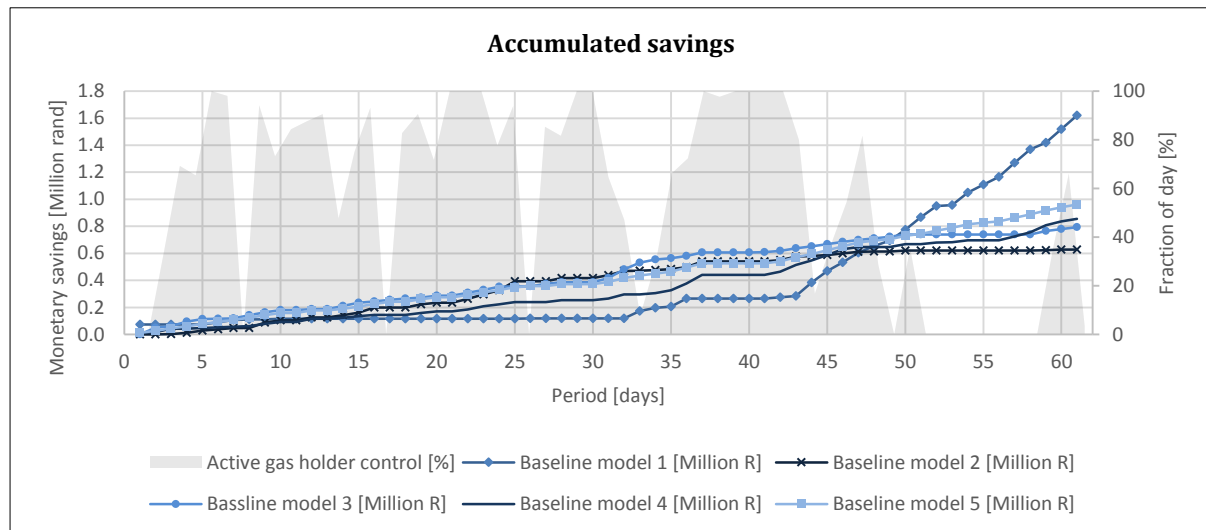


Figure 71: Case study monetary controller benefit Baseline models comparisons

The savings of Baseline model 1 are inconsistently distributed. Baseline models 2 to 5 have a much more consistent savings accumulation for the period. This indicates that the models can measure the controller performance with the system noise. Each of the baseline models differ intrinsically from one other. Therefore, for Baseline model 2 to Baseline model 5, they validate each other.

For this study, the average of the four models is taken as the benefit. The benefit for the controller is, therefore, R0.8 million for two months. The consistent performance suggests that savings will continue to grow at this rate. Therefore, the controller has a projected annual benefit of R4.8 million for the facility presented in the case study.

It is difficult to draw a correlation between the accumulated monetary savings and the portion of the day that the controller actively controlled according to the BFG gas holder level. Baseline model 2 is the only model where the monetary savings are constant from day 50 to day 60. However, this does not confirm a direct correlation. The savings are therefore accountable to both the energy awareness and automated control.

Implementing an automated control like the one presented in this study requires inputs for plant personnel, particularly that of the operators. Working with the operators creates an energy-conscious environment. Additionally, the operators know that their superiors will track the generation performance. Thus, the project did not only deliver an automated controller but made the facility personnel more energy conscious during day to day operation.

4.5 Evaluating project sustainability

A sustainability strategy was implemented after a baseline model was selected. The sustainability strategy consists of a reporting system. The objective of the report is to continuously keep the responsible parties aware of how the controller is performing. Thus the baseline model is the key element of the reports. The plant personnel requested that the five different bases were reported on.

A software package was used to automatically generate daily reports and distribute it to the responsible personnel. Data from the previous day are reported on. Every evening at midnight the data from the plant is received with a File Transfer Protocol (FTP) drive and processed with a Python script. The processed data is imported by the automatic reporting software package where after the software generates the reports and distributes it by email.

The report was sent to the three operators, the responsible technician and production manager. Additionally, the report was sent to the party which implemented the controller. The three operators received the report to improve their own operation. Both the technician and production manager use the report to track the project and ensure that the operators are using it on a daily basis. The facility assigned the production manager to ensure that the controller remained operational.

The report was concise but comprehensive while consisting of two pages. All of the information required to analyse the controller performance of the previous day is on the first page. This was important because of a person being less likely to continuously monitor a report if the information is distributed across several pages.

The second page of the report consisted of data which influences either the by-product gas network or the on-site power generation plant. This information is illustrated by four different graphs. Data plotted included COG and BFG holders, gas sent to the mills, cold blast air of the blast furnace and the COG and BFG sent to the boilers.

4.6 Conclusion

The system evaluation proved that the case study has a suitable by-product gas system for the controller to achieve significant energy savings. A tier based controller was designed. The controller was required to be a tier based to the boilers of the case study becoming unstable with continuously changing electricity generation demand.

The controller was successfully implemented by programming the controller logic directly into the SCADA which the process controllers use. An option to activate or deactivate, as well as control limits were added to the SCADA to ensure safe gas holder operation. The controller was refined according to the process controllers' instructions.

All five baseline models from Chapter 3 were used and developed with a baseline period of a month's data before the implementation of the controller. Actual data from the system after the controller was implemented was used to determine the controller benefit. Except for Baseline model 1, the controller benefit of the baseline model was determined within a $\pm 20\%$ margin of the combined average. The benefit was calculated as just above R800 000 for the two months.

The project sustainability strategy revolved around continual awareness about how the controller is performing. This awareness was achieved using an automated reporting system. The reporting system makes use of specialised software that automatically generates reports on a daily and monthly basis and distributes the reports via email to relevant parties. It is the responsibility of the relevant parties to ensure continuous project performance.

The sustainability strategy identified degradation in the controller's performance after several months of operation. A clear distinction in performance was noticed by the parties checking the automatic reports. An investigation revealed that changes made to the alternator configuration were the result. Modifications were made accordingly allowing the controller to resumed operation at the desired performance.

Chapter 5 – Conclusion and recommendations



Figure 72: Cold rolled flat products⁵

Final conclusions and recommendations for future work

⁵ Unisteel, “Cold rolled coils (flat products)”, [Online]. Available: www.unisteel-international.com/products/13/33/Cold-rolled-coils

5.1 Conclusion

The South African iron and steel manufacturing industry is forced to reduce its energy expenditure for sustainable operations. Electricity is second to coal the largest energy source required in steel making. A typical South African facility can consume 40 MW electricity for daily production. Additionally, South African electricity rates are ever increasing without signs of stabilisation making improved utilisation on the on-site power generation plant attractive.

Imbalances between by-product gas production and consumption make it difficult for a single operator to optimally utilise and balance the by-product gas network holistically. Research proved that much work has been on prediction, scheduling and optimisation models of by-product gas. These models are however, complicated and generally require a sufficient amount of reliable plant data. South African plants suffer a lack of CAPEX, specialised skills and the required data inputs.

This study focused on the development, implementation and measurement of a sustainable controller which increased electricity generation with by-product gas utilisation. The controller was required to function with the minimum amount of plant inputs and be commissioned without any CAPEX. A comprehensive generic methodology was developed to implement such a controller in a suitable facility.

The developed methodology consisted of a three-step system evaluation procedure to ensure that the facility is suitable for the controller. A complete guide to developing the controller with the option of two different control strategies, as well as to simulate the controller on the actual system before implementation. Three different implementation approaches were discussed. Finally, the methodology was concluded on five different baseline models and a project sustainability strategy.

Validation of the study was done by implementing the controller on a case study. Each step of the developed methodology was chronologically followed. The design of the controller was based upon tier control. Implementation was done by coding the controller directly into the SCADA and granting the operators the ability to enable or disable control as required. Limits were given to operators to ensure safe operation of the gas holder.

Difficulties regarding M&V of the controller due to high noise levels led to all five baseline models being used to measure the generation benefit gained by the controller. The baseline models were developed using a baseline period of 1 month prior to controller implementation. Results of two months post-controller implementation were used to determine and compare energy saving achieved by each baseline.

The comparison of the baseline models revealed that four of the five baselines calculated relatively similar savings. As expected, the constant baseline model was not able to accurately quantify the controller's impact. Results of the other four baselines revealed that a monetary saving of more than R4.8 million annually is achievable by the controller.

A sustainability strategy was implemented in the case study. The strategy consisted of an awareness mechanism. Awareness was obtained by utilising an automatic reporting system. Automated reports were generated daily and monthly and distributed to the relevant parties. It was then the relevant parties' responsibility to ensure that the controller is updated accordingly. The sustainability strategy proved successful after the automatic reporting system revealed a degradation in the controller performance leading an updated controller.

5.2 Recommendation for future work

This study serves only as the foundation of a by-product gas controller. Once this foundation has been successfully established, refinements can be made continuously. Improvements that can be made to the development of more effective controller includes:

- Infrastructural valve control improvements;
- Boiler's efficiency incorporation;
- Alternator's efficiency incorporation;
- BFG and COG holder interlinked control;
- By-product gas production prediction models; and
- Fuel gas demand prediction models.

Most of the valves on the gas and steam distribution network are operated with Proportional Integral (PI) controllers. Improvements on these control systems would result in a more refined distribution network. The controller would, therefore, be able to successfully control on a finer resolution level. This type of control might result in the controller being able to utilise by-product gas more effectively.

Varying infrastructural operation efficiencies are present on most typical industrial plants. This is due to different designs, equipment modifications, and extended operating periods. Thus it is typical for plants to have identical boilers or alternators operating at different efficiencies. Future improvements to the controller can include control according to these efficiencies.

Controlling according to either the boilers' or alternators' efficiencies would extend the control to select which component should carry what portion of the load. For example, if boiler A is more efficient than boiler B, then boiler A should be generating a larger portion of the required steam.

This study only looked at a controller on the BFG holder. The reason is that the portion of BFG that was flared was significantly bigger than COG's portion. Some facilities might not have this unbalanced flaring ratio. For plants where a more even portion of COG and BFG are flared, it would be beneficial to design a controller that makes use of both COG and BFG, with the possibility to include BOSG.

A controller operating according to more than just one gas holder would need to consider which by-product gas has the highest influence on energy saving and control according to this parameter. The different gas holders should be balanced with the controller striving towards minimal flare of the higher priority gas first.

The final recommendation for future work is to incorporate by-product gas production and fuel gas consumption prediction models. Including a prediction of by-product gas production to the controller would make it possible for the controller to prepare the gas holder for the prevailing by-product gas condition. This concept is similar for incorporating fuel gas consumption prediction to the controller.

The benefit of being able to prepare the gas holder for the future by-product gas conditions lies in emptying the gas holder as preparation, with excessive electricity, to accommodate significant surplus by-product gas. Therefore, the system would be able to capture more by-product gas before flaring is reached. Similarly, the case holder can be filled up for instances where a shortage of by-product gas is predicted.

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