

Compressed air energy savings on an iron production plant

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ABSTRACT

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In the past several decades, energy efficiency has become increasingly important. A large driver behind this is reducing greenhouse gases that are caused by the combustion of fossil fuels. Most electricity generated in South Africa is from the combustion of fossil fuels.

In South Africa, there is a need for reducing electricity consumption. Since 2008, there has been a significant shortage of electricity in the country. Load shedding was introduced in an attempt to manage the demand. When implementing energy efficiency strategies in South Africa, these strategies will eliminate the electricity shortage and also reduce greenhouse gas emissions.

With the industrial sector being the largest consumer of electricity, it was targeted for improvements in energy efficiency. Strategies to improve the energy efficiency of electric systems have been implemented on various mines. However, the South African steelmaking industry is another large sector that has not received much attention yet.

The steelmaking industry is under great financial pressure due to steel imported from China being cheaper. This led to local consumers importing steel rather than buying locally produced steel. With the steel industry being energy intensive and under financial pressure, it is the ideal place to look for energy efficiency improvements.

Iron production is a large part of steel production. In this study, compressed air energy efficiency strategies are investigated. The most suitable strategy is selected and an implementation strategy developed. The strategy is implemented on an actual iron production plant for the purpose of validation.

The implemented strategy resulted in a significant demand reduction. The cost savings achieved from the reduction can be used to fund further energy efficiency strategies. The final result would be a more energy efficient system, which will decrease production costs. The lower production costs will return or even increase competitiveness in the global market.

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LIST OF ABBREVIATIONS

DCAC	direct contact air cooler
DRI	direct reduction iron
DSM	demand-side management
EAF	electric arc furnace
GVA	guide vane angle
HAZOP	hazardous and operability study
HBI	hot briquetted iron
HP compressor	high pressure compressor
LP compressor	low pressure compressor
PCI	pulverised coal injection
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
VSD	variable speed drive

LIST OF UNITS

kPa	kilopascal
kW	kilowatt
MW	megawatt
Sm ³ /min	standard cubic metre per minute
TWh	terawatt-hours

1 INTRODUCTION

1.1 PREAMBLE

A large amount of energy is consumed throughout the world. Energy has become an important topic worldwide due to conservation for future sustainability. Substantial emphasis is placed on carbon emissions induced by generating electrical energy. There is also only a limited number of energy sources available [1].

Approximately one-third of the world's primary energy consumption is due to the manufacturing industry [2]. Energy requirements of manufacturing processes need to be reduced to ensure sustainable operation. By optimising industrial systems to consume less energy, carbon emissions and strain on energy sources will be reduced.

In this study, an energy saving strategy on the compressed air system of an iron manufacturing process will be investigated. The purpose of this chapter is to:

- Discuss the importance and need for energy management
- Provide general background and identify the need for energy management
- Identify the research aim and objectives

1.2 ENERGY MANAGEMENT

Energy management and greenhouse gas emission have become increasing concerns over the past years. This is due to the increasing price of energy and efforts in sustainable development. Energy has become more expensive due to the decreased availability of energy sources, especially fossil fuels. Several efforts in reducing greenhouse gas emissions are also being made for the purpose of sustainable development [3].

The world population as well as the number of industries are constantly increasing [4]. These two factors result in an increased amount of energy required. In order to manage the available energy sources responsibly, it is important to look for energy saving opportunities. The World Energy Council provides the following definition for energy efficiency [3]:

“Energy efficiency improvements refer to a reduction in the energy used for a given service or level of activity. The reduction in the energy consumption is usually associated with technological changes, but not always since it can also result from better organization and management or improved economic conditions in the sector (‘non-technical factors’).”

The need for energy efficiency improvements has now been identified. However, managing energy would require time, effort and possibly capital from the consumer. Due to electricity generation methods, there are a number of changes that can be made by the supplier to increase energy efficiency. The largest impact can be made by the consumer [5].

Many companies have already made the shift towards sustainability and improved energy efficiency. They have developed an interest in energy efficiency due to the high energy costs that have become a key economic driver. Becoming more energy efficient will not only reduce energy bills, but will also increase profits [6].

A reduction in energy consumption also has an environmental impact. Greenhouse gases generated from fossil-fuelled energy sources are reduced when reducing the energy demand. Reducing greenhouse gas emissions has become extremely important in the past decades. “Clean” production is needed to ensure a sustainable life for the future generation [7].

In South Africa, the difference between supply and demand of electricity has been a concern [5]. In the next section, the reasons for this will be discussed. The commitments that the country made in terms of energy efficiency will also be discussed. In the final part of the section, the solutions that have been identified will be given with a short conclusion at the end.

1.3 THE SOUTH AFRICAN ENERGY SITUATION

The electricity sector is a crucial sector in South Africa. Ninety-five percent of electricity consumed by the South African market is supplied by the state-owned utility Eskom. South Africa has started to suffer from rolling blackouts since the middle of 2000. It seems that Eskom is unable to supply the demand and eliminate the lack of capacity [8].

The South African electricity supply is characterised by outdated structures. The distribution is also centralised and unidirectional from Eskom. Electricity generation is mostly based on using coal. The demand for electricity has become higher than the capacity of Eskom, which led to a backlog in electricity supply [9].

A possible reason for the backlog may be due to the low and stable prices of electricity in the past. Energy efficiency was not a concern since electricity was available at a low price. This resulted in the country becoming electricity intensive [3]. Once the demand could not be met any more, electricity prices started to increase at a rapid rate. The major factors that determined the rate at which the price increased are [7]:

- Production changes
- Changes in the structure of the economy
- Efficiency improvements

At the beginning of 2008, the backlog resulted in an electricity shortage. The shortage had consequences for the South African economy. A solution to the problem had to be found urgently to minimise any further damage. In previous studies it was found that the initial price increases did not have a large effect on consumption. However, as the price kept on increasing, the consumer's sensitivity to the electricity price increased. This resulted in demand-side savings due to consumers reducing consumption or finding alternative sources of energy [5].

South Africa has several economic problems which have a negative impact on the country. Some of these problems include [4]:

- Energy challenges
- Old and inadequate infrastructure
- Inefficient regulatory processes delaying international and local investments
- Inefficient government coordination, long-term planning and vision

In an attempt to maintain a supply to the manufacturing industry, the residential supply is reduced. A load-shedding initiative was created in which residential electricity is switched off during times of high demand [4]. Additionally, a demand-side management (DSM) initiative was developed. In this strategy, industrial consumers receive compensation when a reduction in electricity consumption is shown [10].

In 2015, it was estimated that the annual electricity demand in South Africa would grow from 345 TWh to 416 TWh by 2030. The expected growth according to the National Development Plan is 5.4%. A large amount of money will be spent on generating clean energy since 85% of electricity is generated from coal-fired plants. Considering the proven coal reserves of 8% in South Africa, as shown in Figure 1, this is an important step towards sustainability [4].

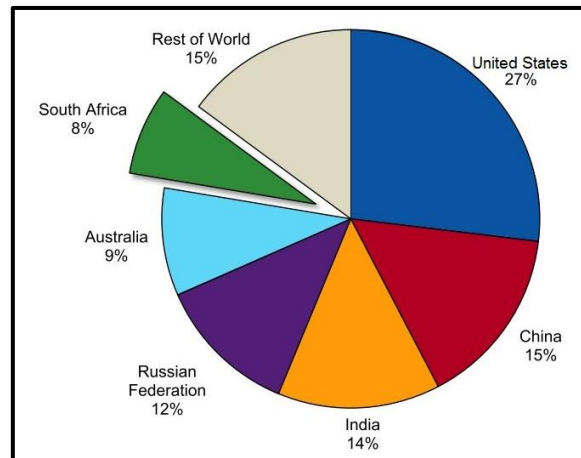


Figure 1: Proven coal reserves (adapted from [4])

In 2010, the South African government made a commitment to the Secretariat of the United Nations Framework Convention on Climate Change to reduce greenhouse gas emissions with 34% by 2020 [7]. This commitment comes at a price of US\$30 billion, which will be used for building new power stations. These power stations include Medupi and Kusile situated in the Limpopo and Mpumalanga provinces of South Africa respectively [4].

Figure 2 shows the annual energy flows for South Africa as in 2012. From the figure it can be seen that the largest amount of energy is from coal production. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) was developed to assist in changing this. In this programme, subsidies are given to large-scale grid-connected renewable energy systems [9].

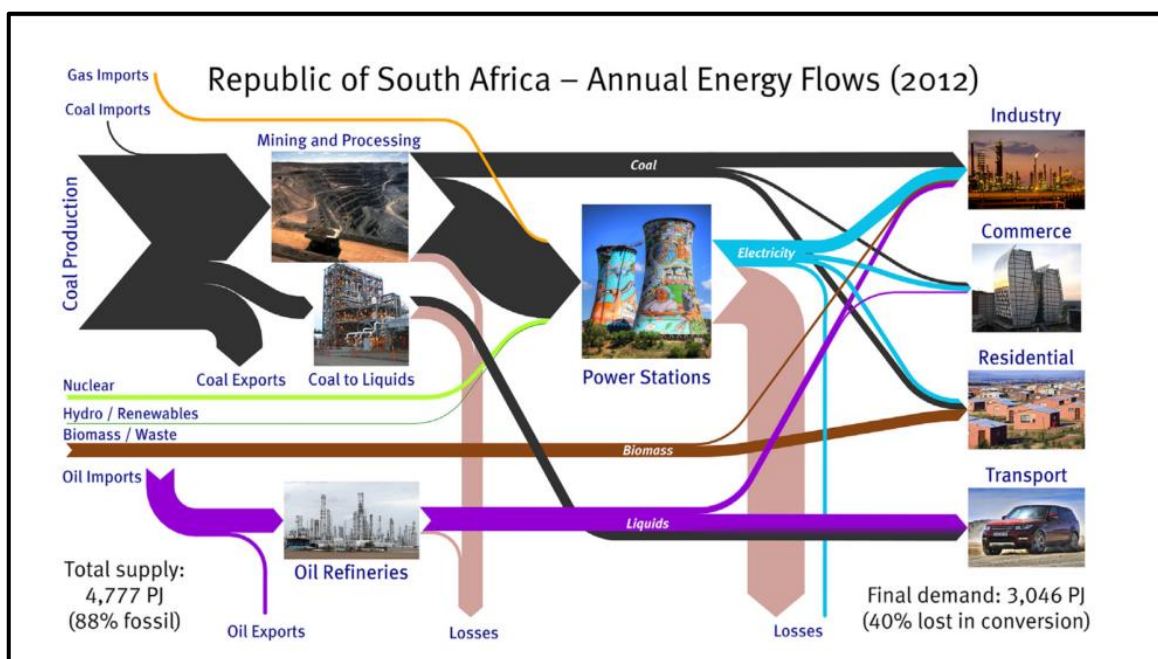


Figure 2: South African annual energy flows as in 2012 [4]

Not only does REIPPPP reduce the reliance on coal, but the programme also creates an opportunity for the private sector to supply electricity. This programme is also assisting in reducing the backlog in electricity supply that developed over several years. As a further advantage of REIPPPP, a reduction in greenhouse gas emissions is also realised when reducing coal reliance [9].

South Africa requires a large effort to catch up and compete with other energy efficient countries. A large investment in power generation infrastructure in the short term will have a significant impact on the manufacturing capital costs. The end result will be an increase in competitiveness in the global market [4].

1.4 OVERVIEW OF STEELMAKING

1.4.1 Steelmaking process

The process of steelmaking is energy intensive. The steelmaking industry consumes approximately 20% of all industrial energy consumed. Due to the amount of energy required, a large amount of carbon dioxide is released into the atmosphere. The carbon dioxide released is due to combustion processes required for energy generation [2].

Steel production is a very important industry and, therefore, several new ironmaking processes have been developed over the past decades. The most common processes are [11]:

- Blast furnace and basic oxygen furnace process
- Direct reduction iron (DRI) process
- Electric arc furnace (EAF) process

The preferred method is the blast furnace–basic oxygen furnace process. In this process, the blast furnace reduces iron ore to liquid iron. Carbon in the form of metallurgical coke is used as the reductant and energy source. Since the reduction process requires large amounts of energy in the form of heat, pulverised coal injection (PCI) is also used [11].

The coke is added at the top of the furnace with the iron ore, while the pulverised coal is injected at the bottom of the furnace with the blast air [12]. After reducing the iron ore, the iron is converted to steel using the basic oxygen furnace. This process mostly produces flat products for construction, welded pipes and ship building. [11].

In the DRI process, the requirement for coke is eliminated. The iron ore is directly reduced to metallic iron by using coal gas or natural gas as the reductant. This produces a product

known as hot briquetted iron (HBI). Figure 3 shows a schematic illustration of the DRI process [11].

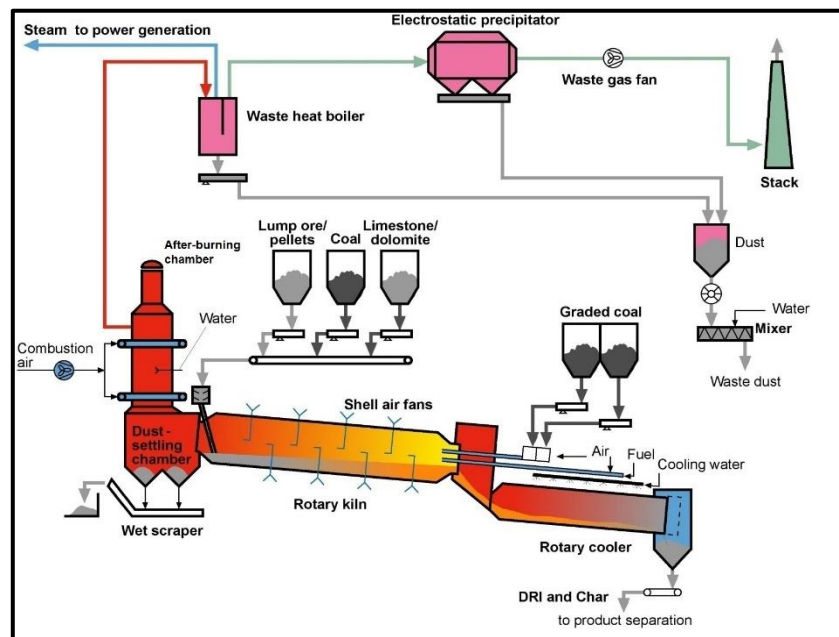


Figure 3: Schematic of the DRI process¹

An EAF is mostly used to produce long products for construction, wire-drawn products and automotive applications. The advantage that the EAF process has over the other processes is that it can use recycled scrap. HBI from the previous process can also be used alone or in combination with recycled material in this process. Figure 4 shows a typical EAF in operation. [11]



Figure 4: An EAF in operation²

¹ Outotec, [Online]. Available: <http://www.outotec.com/Global/Products%20and%20services/Direct%20reduction/SL-RN-flowsheet.jpg>. [Accessed 27 08 2016].

² Pasargad Tahlil, [Online]. Available: <http://pasargadtahlil.com/File/GetFile?id=9cc30065-7c44-44dc-af9d-743008012776>. [Accessed 27 08 2016].

This study concentrates specifically on the compressed air supply to a blast furnace. A method for improving the energy efficiency of the compressed air system used in ironmaking needs to be found. An introductory discussion of the operation of a blast furnace is given in Section 1.4.2. A more detailed discussion is given in Section 2.2.

1.4.2 Blast furnaces in ironmaking

As mentioned in the previous section, steelmaking requires a large amount of heat energy. Included in the steelmaking process is the ironmaking process. As discussed in Section 1.4.1, iron is produced in a blast furnace before it can be converted to steel in a basic oxygen furnace. The blast furnace–basic oxygen furnace process is responsible for approximately 70% of crude steel manufacturing [2]. Figure 5 shows a picture of a typical blast furnace with some of its auxiliaries also shown.

The raw material (iron ore and additives) is hoisted from the stock house to the top of the blast furnace. The coke is also transported to the top of the furnace using the same process. At the top of the blast furnace, a pressure-equalising mechanism is used to drop the materials into the furnace. The pressure-equalising mechanism is required since the furnace operates at a pressure higher than atmospheric pressure [13].



Figure 5: Typical blast furnace with auxiliaries³

³ Hotwork, [Online]. Available: <http://www.hotwork.com/wp-content/uploads/2015/12/pic-blast-furnace-3.jpg>. [Accessed 27 08 2016].

The energy for blast furnace operation is provided by coke added to the top of the furnace and pulverised coal injected at the bottom with blast air. For blast furnace operation, a large volume of compressed air, known as blast air, is required. The main purpose of the compressed air is to supply the combustion process with oxygen [12].

The compressed air system of a blast furnace is the largest consumer of electricity in the ironmaking process. Thus, the compressed air system needs to be optimised to ensure efficient operation and sustainability. By doing this, carbon emissions from the ironmaking process can also be reduced. Globally, the reduction of carbon emissions is considered to be very important [2].

The hot outlet gases coming from the top of the blast furnace go through a dust catcher to remove most of the solid waste. After the dust catcher, the gas is cooled and further cleaned in other processes to remove finer impurities. In these processes, the pressure is also significantly reduced [14].

The resulting gas has energy potential and is, therefore, delivered to other processes. At these processes, the gas, as a source of energy, is combusted. Some of the processes are heating of the blast furnace stoves and steam generation at the boiler plant [15]. The operation of the blast furnace stoves will be discussed in Section 2.2.

In the next section, a general discussion on compressed air and its application in the ironmaking industry will be given. From the discussion, the need for this study will be identified.

1.4.3 Compressed air in ironmaking

Compressed air is commonly used in industry due to the simplicity and safety in production and handling thereof [16]. Although compressed air is used across a wide range of industries, it is considered to be one of the most expensive sources of energy [17]. This is since a well-designed compressed air system is only 11% energy efficient [18].

The reason for the low efficiency is illustrated in Figure 6. From the figure it can be seen that only a small portion of the total energy is available to the end consumer due to losses. A substantial amount of electricity generated worldwide is used for the purpose of compressing air [19].

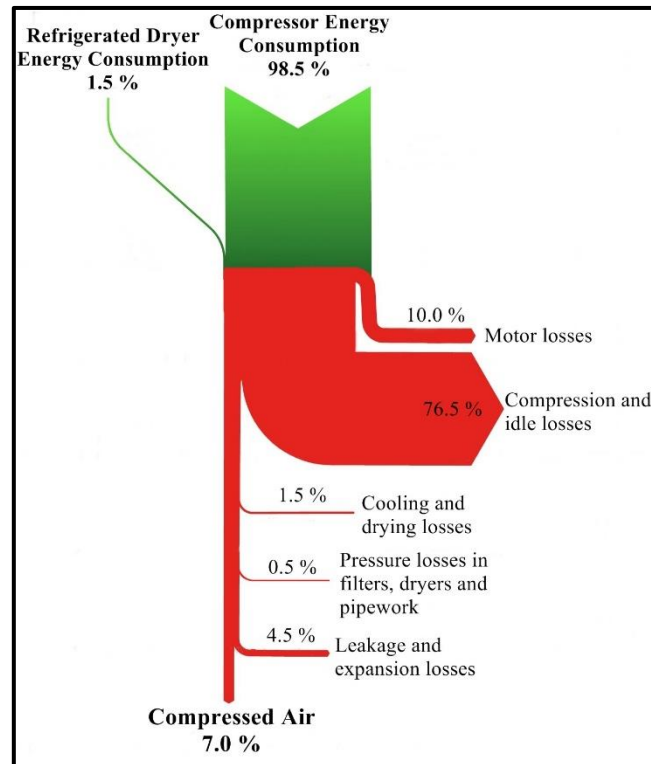


Figure 6: Energy flow of an inefficient compressed air system (adapted from [20])

For a system with such low efficiency, strategies for improving the energy efficiency might be possible [21]. Improvements in energy efficiency of a compressed air system could result in energy savings of 20–50%. The largest reason for inefficiency is due to air leaks, poor system maintenance and misuse of compressed air [17].

As mentioned in Section 1.4.2, blast furnaces require large volumes of compressed air to operate. This is part of the reason why the ironmaking process is very energy intensive. Due to the requirements of blast furnaces, centrifugal compressors are commonly used in ironmaking. Centrifugal compressors have a higher efficiency as well as a wider range of flow than other types of compressor [22]. More detail will be provided on the amount of volume flow that is required by a blast furnace in Section 2.2.2.

From the above it can be seen that compressed air systems have large potential for energy efficiency improvements. The ironmaking process is a large consumer of compressed air used as blast air. Instrument air is usually at a higher pressure and generated separately. This makes the ironmaking industry the ideal industry for investigating energy savings. There has been numerous compressed air saving strategies implemented on mines. There is, however, limited information available on compressed air energy savings in the ironmaking industry.

The focus of this research is the implementation of a compressed air energy saving strategy on an iron production plant. This requires investigating compressed air energy saving

strategies in general, and strategies used in other industries such as mining. The strategies then need to be adapted according to the requirements of the iron production plant.

1.5 RESEARCH OBJECTIVES

In this section, the different research objectives will be discussed briefly:

Research into ironmaking

This is the starting point of the study. A short overview of the steelmaking process needs to be given. Ironmaking is only a part of the steelmaking process. More detailed background on ironmaking and the need for compressed air is required. Significant attention will be given to the blast furnace process since it is the largest consumer of compressed air in the ironmaking industry.

Use of compressed air systems

General background on typical compressed air systems is given. From this, the different components of the system are identified. When considering the different components and the system as a whole, energy saving opportunities can be found.

Identify compressor energy saving strategies

After considering compressed air systems in general, strategies for improving energy efficiency can be identified. General compressed air saving strategies are identified from previous studies. The possible impact on energy efficiency of each strategy also needs to be identified.

Identify the critical parameters in ironmaking

The ironmaking process has strict requirements in terms of operation. These requirements need to be identified to determine a suitable compressed air energy saving strategy. The strategy should result in energy efficiency, without having a negative impact on ironmaking.

Derive an energy saving strategy and implementation procedure

As a case study, an energy saving strategy will be implemented on an actual ironmaking plant. Before implementation, a proper strategy and implementation procedure need to be developed. All the requirements for implementing such a strategy on an ironmaking plant need to be met.

Implement the best-suited strategy

This is a critical part of the study. Here it is determined if the developed strategy can be implemented on an actual ironmaking plant. The necessary procedures of implementation need to be followed to ensure that the strategy is implemented safely and sustainably.

Determine the sustainability of the strategy

The final objective of the study is the interpretation of the results. It needs to be determined if the implemented strategy delivered the desired results in terms of energy efficiency. It also needs to be determined if the strategy is sustainable in the long term. In the final chapter, some recommendations are given on how to increase the energy efficiency and sustainability.

1.6 DISSERTATION OVERVIEW

This section provides a short overview of the contents of each chapter:

Chapter 1

This chapter provides general background on the components relevant to the study. It also gives background on what led to the study. An important part of this chapter is the study objectives. The identified objectives are discussed shortly and form the backbone of the study.

Chapter 2

Chapter 2 provides more detailed background on the components that will be considered in this study. Detailed background on the operation and processes of a blast furnace is given. Detailed background on typical compressed air systems and compressors are also given. The important part of this chapter is identifying possible energy saving strategies on compressed air systems. In the final section, a literature review on previous studies is done.

Chapter 3

In this chapter, the information gained from Chapter 2 is used to develop an energy saving strategy that can be implemented. In the introduction of this chapter, a generic methodology for implementing an energy saving strategy on an ironmaking plant is presented. In the sections following the introduction, the methodology is applied to an actual system. This is to test the validity of the methodology and also to illustrate its application.

Chapter 4

The fourth chapter contains the results of implementing an energy saving strategy on the compressed air system of an ironmaking plant. The results show if the desired results were obtained. In this section, verification and validation through a case study is also done. From verification and validation, it is found that the developed strategy is successful in achieving the desired energy savings.

Chapter 5

The final chapter concludes the study. In this chapter it is determined if the study is successful in achieving the objectives as stated in Chapter 1. Additional to this, a recommendation is given on further increasing energy efficiency and sustainability.

1.7 SUMMARY

In Section 1.2, a discussion on energy management was given. Background on the South African energy situation was also discussed in Section 1.3. In Section 1.4, basic background was given on the steelmaking industry in terms of ironmaking and compressed air usage.

It was noted that energy usage has become a global concern. The two major reasons are availability of energy sources and greenhouse gas emissions. From Section 1.3 it became clear that South Africa is in need of energy savings – especially in the electricity sector.

The research objectives section followed the energy management and background sections. In this section, the objectives of this study were identified and discussed shortly. A dissertation overview was given in the next section.

In Chapter 2 more detailed background will be given on the steelmaking industry, specifically the ironmaking process. Background on compressed air systems and its various components will also be discussed. After this, the possible energy saving strategies that can be implemented on compressed air will be identified. In the final part, a literature review will be done on previous studies regarding compressed air energy savings.

2 COMPRESSED AIR USAGE IN IRONMAKING

2.1 PREAMBLE

In the previous chapter some of the different methods of iron production were identified and discussed shortly. Blast furnaces are most commonly used in South Africa. A blast furnace consumes large amounts of compressed air. This creates an opportunity for energy savings on the compressed air system of an iron production plant.

In this section, the operation of a blast furnace will be discussed in more detail. The operational requirements and restrictions that were identified will also be discussed. An overview of a typical compressed air system will also be given. The final part of this section identifies the different compressed air saving strategies for any compressed air system, followed by a short summary.

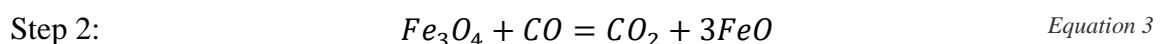
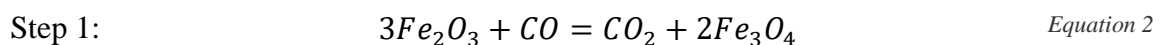
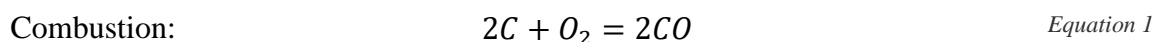
2.2 BLAST FURNACE OPERATION

2.2.1 Overview of operation

The purpose of a blast furnace is to chemically reduce iron ore to liquid iron. Magnetite and hematite are the most commonly used types of iron ore since they can be added directly to the furnace. Some of the other types of ore used in ironmaking need to be processed before they can be used in the furnace [23].

A large amount of energy is required to reduce iron ore to liquid iron. The required energy comes from the combustion of carbon. The carbon is in the form of coke or pulverised coal. The coke is solid carbon that is added at the top of the furnace while the pulverised coal is injected with the blast air at the bottom of the furnace [12].

Carbon monoxide also forms during the combustion process. Carbon monoxide is the reducing agent and is, therefore, very important for the reduction process inside a blast furnace. The reduction process can start after the combustion process. The reduction process takes place in several steps and the basic chemical formulas are [24]:



Step 3: $FeO + CO = CO_2 + Fe$ or *Equation 4*

$FeO + C = CO + Fe$ *Equation 5*

Equation 2 and Equation 3 are the first two steps in the reduction process. In these two steps, the iron oxide (Fe_2O_3) added to the furnace is reduced to ferrous oxide (FeO). The reduction is due to the high temperature generated from combustion and the presence of carbon monoxide (CO), which forms during the combustion process [24].

In Step 1, the hematite is converted to magnetite. When magnetite ore is used as raw material, Step 1 is not needed. The process then starts at Step 2, thus reducing the amount of energy required. As shown in Equation 4 and Equation 5, the final step is for the ferrous oxide formed during Step 2 to be reduced to liquid iron. This is achieved by reacting with either carbon monoxide or carbon [24].

The end result is liquid iron that can be tapped from the bottom of the blast furnace using the tap hole. The liquid iron produced by the blast furnace is often referred to as hot metal or pig iron. In order to achieve the above chemical reactions, a complex chemical process needs to be completed. A blast furnace is designed for the purpose of completing this complex process under controlled conditions [15].

A typical layout of a blast furnace and its required components are shown in Figure 7. It can be seen from the figure that the furnace requires several additional components for operation. The most important components are as follows [23]:

- Blast furnace
- Stoves
- Stock house
- Skip hoists
- Cast house
- Dust catcher

The blast furnace is the main component, which reduces the iron ore to liquid iron. The blast furnace can be seen as a pressure vessel that operates at a high temperature. As already discussed earlier in this section, the high temperature is generated from combustion of carbon, which also produces carbon monoxide. The heat and carbon monoxide are required for reduction of iron ore [12].

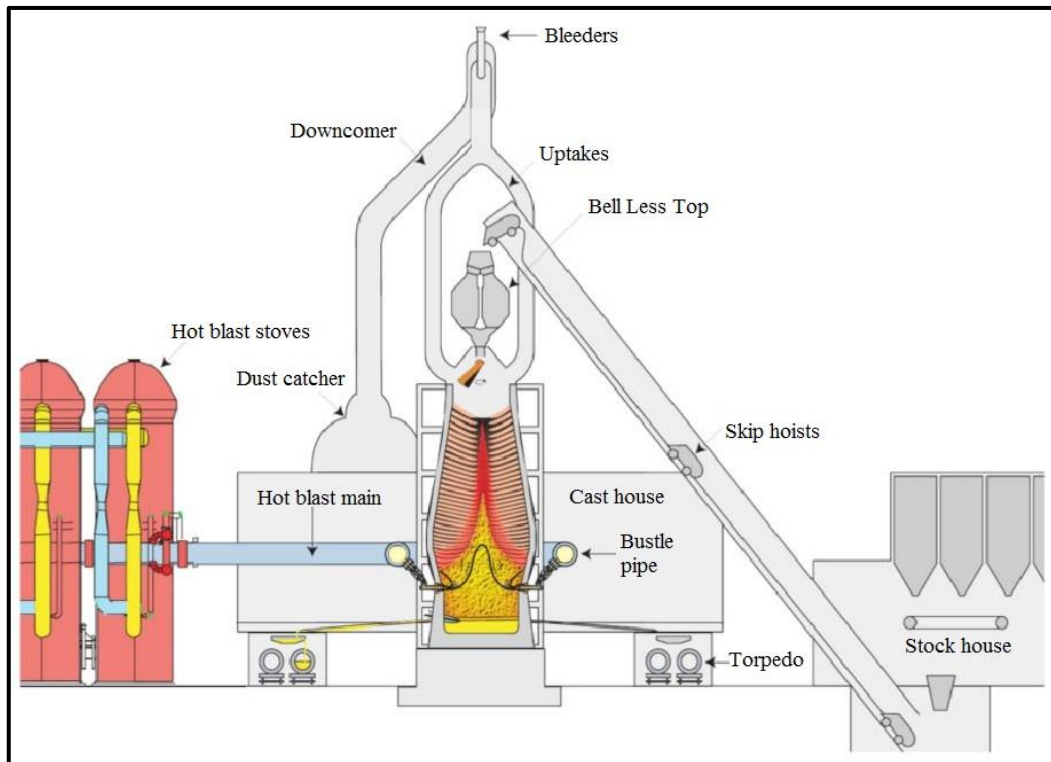


Figure 7: Typical layout of a blast furnace and its required auxiliaries (adapted from [23])

At the stock house, various raw materials required for blast furnace operation are kept in hoppers. These hoppers are continually filled from the stockpile to ensure a continuous supply of material to the furnace. A conveyor belt system is used to transport the correct amount of each raw material to the weigh station of the furnace. The raw material, which includes the iron ore and coke (fuel), is hoisted from the stock house to the top of the furnace using skips. In some cases, a specially designed conveyor belt can also be used [23].

The raw material is fed into the furnace through a Bell Less Top®. This top section of the furnace is used for the purpose of pressure-equalising. Since the furnace is at a higher pressure than atmosphere, the raw material is fed into the furnace through a chamber [13].

At first, the bottom part of the chamber is closed and the top part opened to fill the chamber with material. Once the chamber is full, the top part is also closed and the pressure inside the chamber is increased to match the furnace pressure [25].

In most cases, nitrogen is used for pressure-equalising. After equalising the pressure, the material is dropped into the furnace with a chute. The chute has a circular as well as an up-and-down motion. By controlling the position and angle of the chute, the material is added to specific parts of the furnace. Figure 8 shows a schematic of a typical chute inside a blast furnace with the operation angles also shown [13].

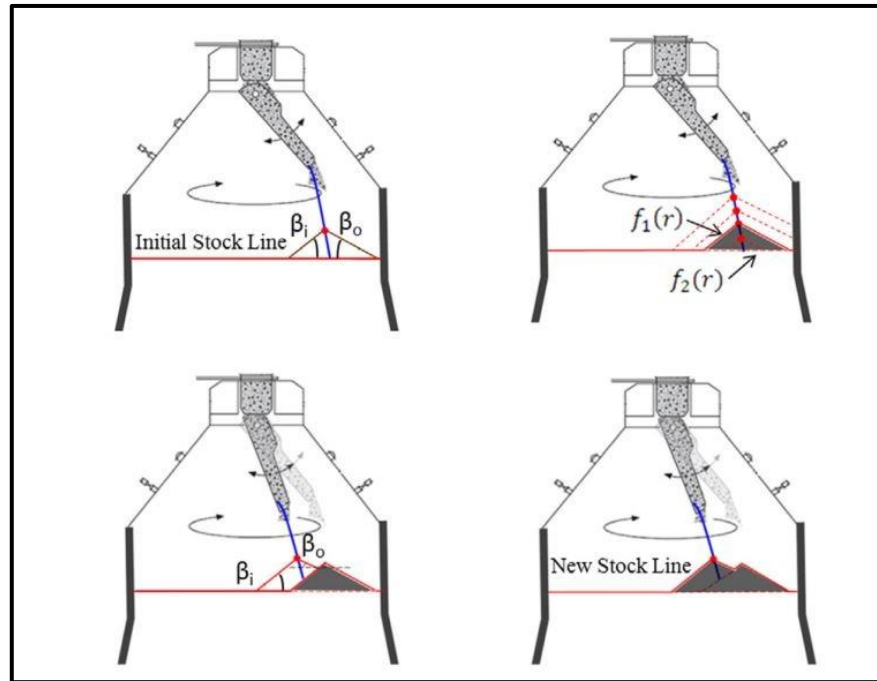


Figure 8: Material loading chute (adapted from [13])

Also seen in Figure 8 is the stock line. The stock line is the maximum height to which the furnace should be loaded. The furnace has a reference from which the stock line is specified. As the iron ore is reduced, the material inside the furnace descends. When the material level at the top of the furnace falls below the stock line, more material is added. The loading of material is a continuous procedure; the rate is dependent on the iron production rate [13].

Due to the high temperatures required in the furnace, the blast air is preheated using stoves. A typical blast furnace requires at least three stoves for normal operation. As shown in Figure 9, a blast furnace stove consists of three different sections [2]:

- Combustion chamber
- Dome
- Checker work chamber

Blast furnace waste gas with an enrichment gas is combusted inside the combustion chamber of the stove. The hot flue gas then travels upwards through the combustion chamber to the dome and down through the checker work chamber. The checker work chamber is filled with refractory bricks through which the gas flows. The chamber is constructed in such a way to maximise the surface area for heat transfer and has a large volume for energy storage [2].

The need for three stoves is due to the cyclic operation to ensure a constant flow of blast air. Only one stove is on blast, which means that it provides hot compressed air between 1 100 °C and 1 250 °C to the blast furnace [12].

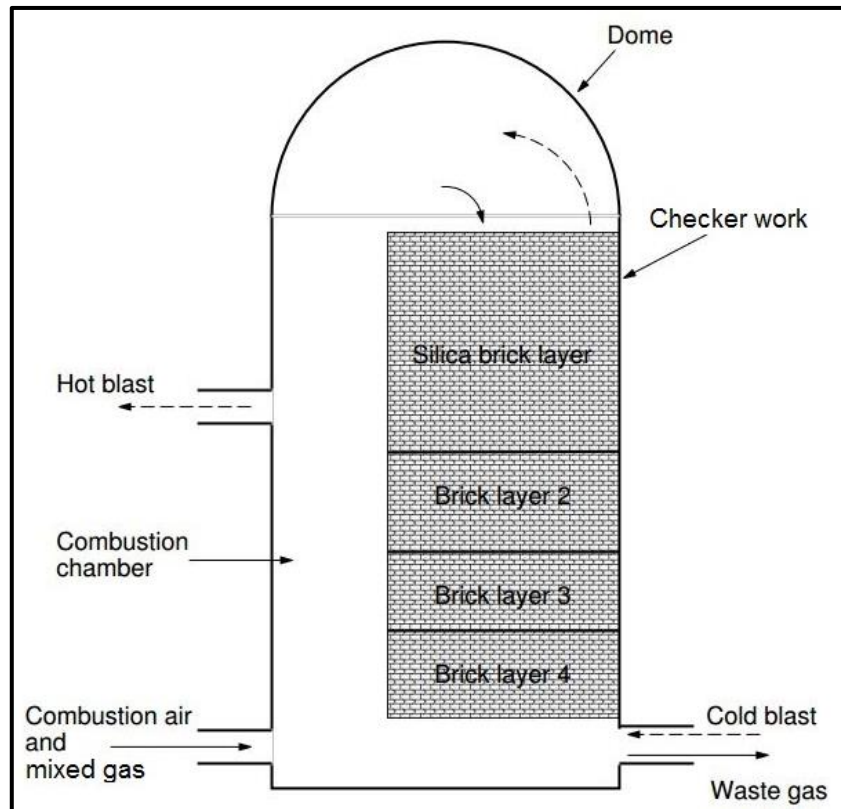


Figure 9: Blast furnace stove (adapted from [26])

The cold blast air supplied to the stove first travels through the checker work, then the dome and finally through a part of the combustion chamber. The other two stoves are said to be on gas, which means they are being heated as discussed in the previous paragraph [2].

It must be noted that a blast furnace stove can only be on gas or on blast. It is not possible for these two processes to take place simultaneously in one stove. Figure 10 shows the typical configuration of a blast furnace stove-piping system. It can be seen that there is a bypass for the cold blast air. This cold blast air is mixed with hot blast air in a mixing chamber to regulate the air temperature. The amount of cold blast bypass air required is reduced as the stove cools over time [2].

The cast house is designed to complete the final step in ironmaking, which is the casting of the molten iron into torpedoes. The molten iron flows out of the blast furnace through the tap hole into the trough, which is part of the cast house. In the trough, the slag is separated from the molten iron. The molten iron is poured into a torpedo, which is located underneath the cast house. The molten iron is then transported on a railway to the secondary processes [23].

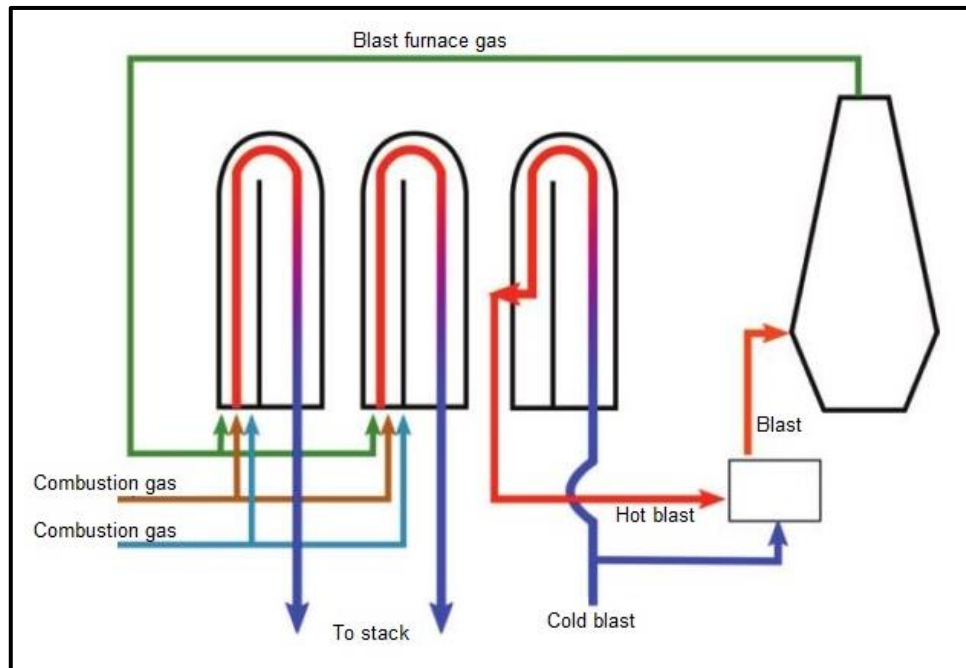


Figure 10: Blast furnace stove-piping layout [2]

The slag that was separated from the iron follows a different path to the end consumer. The slag is quenched in the granulation plant to form granules. These granules are then cooled properly and placed on a conveyor belt. The conveyor belt will lead to a stock pile or directly to the consumer [27].

Slag is commonly used by cement plants to produce cement. If slag cannot be sold to a cement plant, it needs to be disposed. This is not preferred since it is harmful to the environment and is not cost effective [28].

The last component that was listed is the dust catcher. The purpose of the dust catcher is to remove any solid impurities from the blast furnace off-gas. The blast furnace off-gas flows from the top of the furnace to the dust catcher through the downcomer. The dust catcher is only the first step in the cleaning of gas [14].

After the dust catcher, there are other more complex components that cool and wash the gas. One of these components is commonly referred to as the “scrubber”. The hot gas travels through a shower of water that cools the gas and removes small solid particles. Once the gas is cooled, it can go through the final stages of filtering after which it is supplied to various consumers such as the blast furnace stoves [14].

This section only gave a general overview of the blast furnace operation. In the next section more detailed information will be given. From this the importance and impact of compressed air supply will be given.

2.2.2 Operational requirements and restrictions

In the previous section a general overview of blast furnace operation was given. However, blast furnace operation is a sensitive and complex process. In this section more detail will be given in terms of operational requirements. Additional to this, the restrictions that will affect the cold blast air will also be discussed.

The correct loading of a blast furnace is critical to its operation [25]. The loading of the furnace is determined by a loading profile. The correct loading of the furnace is very important since it determines the formation, shape and location of the cohesive zone. These directly influence the gas flow through the furnace as well as the furnace efficiency [29].

The operations staff decide on a specific loading profile according to the desired results. From this, a load program is developed to achieve the desired profile. This is another complex theory that will not be discussed further. It has, however, been established that intermittent layers of iron ore and coke provide the best results [13].

The load profile program is loaded onto the blast furnace control system to automatically load the furnace according to the program. The program has a certain number of steps that state the combination and amount of the different materials to be loaded in that step. Once the program reaches the final step, it restarts at the first step. The program will continue to repeat until a new program is loaded.

The combination of materials as loaded in the furnace is referred to as the “burden”. Figure 11 shows a typical burden distribution inside a blast furnace. In this figure, it can be seen that the materials are loaded in intermittent layers of iron ore and coke. This type of layering can also be referred to as Chevron stacking.

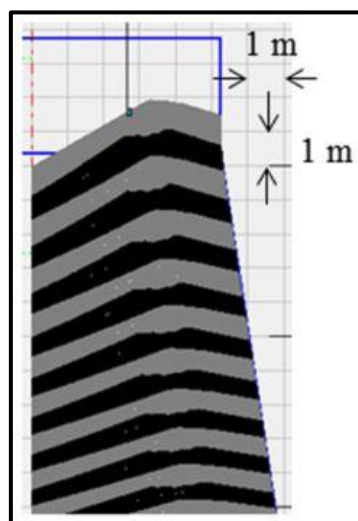


Figure 11: Typical burden distribution inside a blast furnace [13]

The burden has a large impact on blast furnace operation. If loaded correctly, the blast furnace will remain stable for long periods of time. Since experimental work needs to be done for improvement, it does sometimes happen that the burden causes instability. A factor that cannot always be controlled by burden distribution is the condition of the raw material.

Although burden is also loaded according to size, it sometimes happens that large pieces break into smaller pieces. This becomes a critical factor in the control of the furnace. Due to the materials causing a flow restriction, the combustion gases have a pressure drop when travelling through the furnace. The finer the burden material, the higher the pressure drop will be due to limited space for the gases to travel through [30].

The pressure drop is controlled to regulate the velocity of air entering at the tuyères. The pressure drop cannot be controlled directly. For this reason, a specific flow rate is matched with a furnace top pressure. The top pressure and pressure drop combined result in the hot blast pressure required. This places a restriction on the minimum pressure that can be supplied by the compressor plant.

In the case of a differential pressure becoming too high, adjustments need to be made to reduce the pressure. A solution is to “shake” the furnace. When shaking the furnace, the blast air is suddenly removed for a certain period and then returned to normal. The sudden change is achieved by using a “snort” valve. A large amount of air is vented through the snort valve, located before the stoves, thus reducing the amount of air reaching the furnace.

The result is a redistribution of the burden. This assists with decreasing the pressure drop but creates an unknown burden distribution and undesirable mix of solids and liquid in the furnace hearth. The result is that the predictability and stability of the furnace further decrease. Another factor that could cause a redistribution of the load is the presence of a “scab” [13].

A scab is a large piece of solid material that forms inside the furnace. It usually forms on the side of the furnace due to build-up. Similar to this is erosion of the refractories on the side of the furnace. Both situations cause irregular flow patterns, altering the velocity at which the material descends in that area. The final result is the redistribution of the load profile, which could cause furnace instability [13]. Figure 12 shows the presence of a scab and the resulting flow patterns.

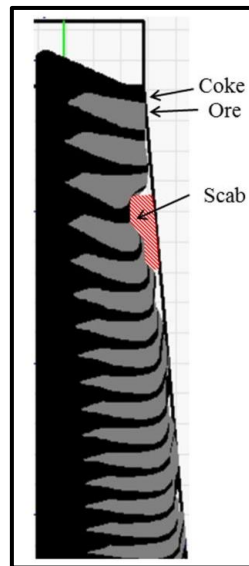


Figure 12: Flow patterns resulting from the presence of a scab [13]

Another important factor in blast furnace operation is a reliable and constant flow of compressed air. Typical blast furnaces consume compressed air at a flow rate of between 1 500 Sm³/min and 4 200 Sm³/min depending on their size. The pressure at which the air is supplied ranges from 100 kPa to 350 kPa, also depending on size. The larger the furnace, the higher the flow rate and pressure will be.

The supply needs to be highly reliable since an interruption in the air supply could result in the furnace having to stop. The required flow rate is specified by the furnace by using a set point. The actual airflow rate needs to be as constant and as close as possible to the set point. If there is a large variation in airflow rate, it could cause furnace instability. When the furnace becomes unstable, the production rate is decreased while the furnace is stabilised.

An iron production plant is largely production-driven due to the high costs associated with production. Therefore, it is important that air is always supplied when it is required. In the case of a set-point change, the actual flow rate needs to reach the set-point value as soon as possible. If the air supply to the furnace is not as required, it could result in production losses and large financial impacts.

When a stove is changed from gas to blast, it usually causes a disturbance in the air supply. This is the case for a blast furnace that is supplied from a single compressed air line. The increased demand to fill the stove with compressed air causes a pressure drop in the supply. Depending on the specific system, the increased demand can be in the range of 400 Sm³/min. The entire system needs to be adjusted as needed to ensure that the effect of stove-filling is minimised.

The air supplied by the compressor plant does not pass through an aftercooler before it is transported to the stoves. The transport pipelines are also heat-insulated to conserve the maximum amount of heat. The temperature of the air delivered to the blast furnace stoves depends on the specific system.

The hot blast air is injected into the furnace using a tuyère. This is also where PCI for combustion takes place. There is a “lance” inside the tuyère through which the pulverised coal is injected. Along with pulverised coal, oxygen is also injected for the purpose of enrichment. PCI is required to reduce costs and also to maintain steady production [31].

The proper design of a tuyère and all of its components is a complex process that ensures optimal combustion and furnace operation. Due to the complexity, the design will not be discussed in this study. Figure 13 shows a three-dimensional representation of a typical tuyère from which the lance can also be seen. The cooling water is used to cool the lance inside the tuyère [32].

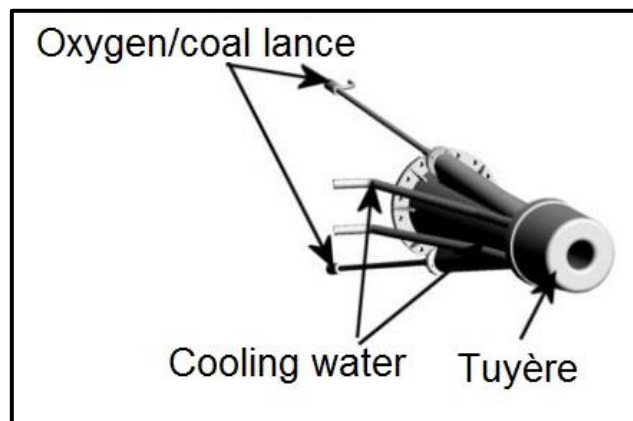


Figure 13: Three-dimensional representation of a tuyère (adapted from [32])

The highest temperature is at the bottom of the furnace where combustion takes place. Due to the high temperature, this is where the final step in the reduction process takes place. As the combustion gases move upwards through the burden, the temperature decreases. Step 1 and Step 2 in the reduction process take place higher up in the furnace due to the lower temperature requirement. The blast furnace process can be considered as indirect reduction when compared with the DRI process [24].

From this section it can be concluded that although ironmaking with a blast furnace is preferred, it remains a complex procedure. The operational requirements place several restrictions on the compressed air supply. They are:

- Minimum supply pressure is determined by furnace operation
- Airflow needs to be supplied according to furnace requirements
- Compressed air supply needs to be highly reliable
- The necessary adjustments need to be made for stove-filling
- The pressure drop due to the snort valve opening needs to be considered

Compressed air systems will be discussed in the following sections. The discussion includes an overview of these systems as well as a short discussion on different types of compressor. Finally, the different energy saving strategies that can be implemented on a compressed air plant will be discussed.

2.3 OVERVIEW OF COMPRESSED AIR SYSTEMS

Figure 14 shows a general layout of a typical compressed air system. The components of such a system can be divided into three major groups [21]:

- Compressed air production plant
- Distribution system
- Application equipment

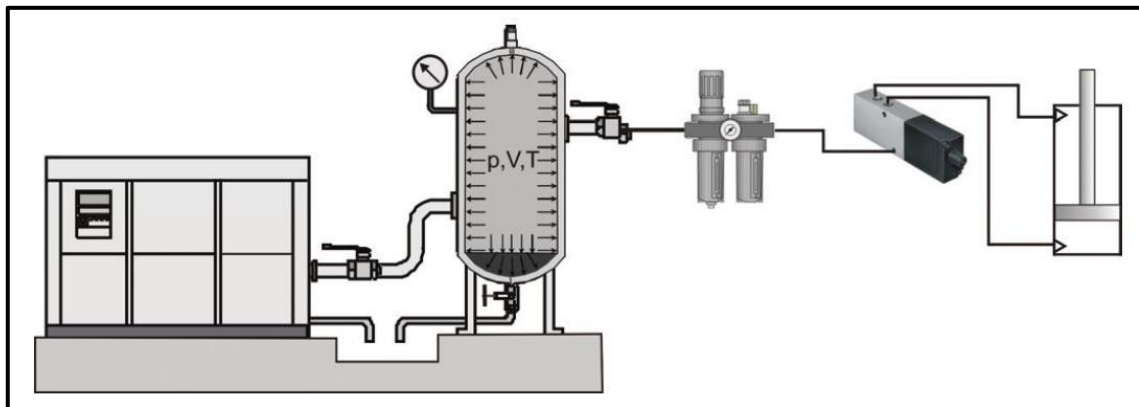


Figure 14: Simplified general layout of a compressed air system [21]

Different components are required within each of the groups above. Some of the general components of such a compressed air system are given in Table 1. A short discussion on the different components from each group will also be given.

Table 1: General components of a compressed air system [21]

Compressed air production plant	Distribution system	Application equipment
<ul style="list-style-type: none"> • Inlet air filters • Compressors • Intercoolers and aftercoolers • Air cooling and drying system • Cooling towers 	<ul style="list-style-type: none"> • Pipes • Valves • Storage/surge tanks • Water traps • Pressure regulators 	<ul style="list-style-type: none"> • Actuators • Air nozzles • Pneumatic drills • Air-levitated bearings

Compressed air production plant

The compressed air plant is the left part of Figure 14. This part of the system takes air from the atmosphere, compresses it, and cools and dries it, so that the air can be supplied to the consumers through the distribution system. A more detailed layout of the compressed air plant is given by Figure 15.

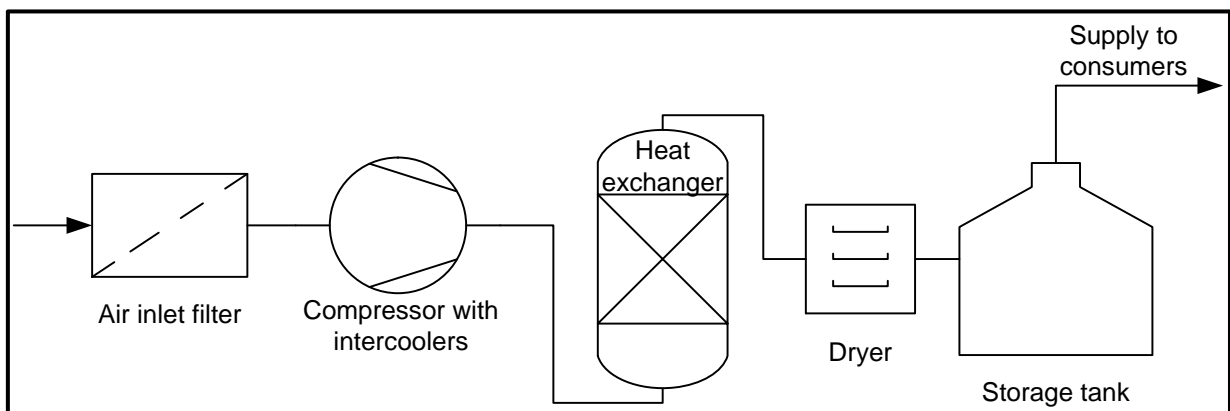


Figure 15: Compressed air plant layout

In order to ensure good quality air and minimise the required maintenance, a good quality inlet filtering system is required. The filtering system needs to minimise the amount of impurities that are able to come into contact with the compressors. Any impurities that are able to reach the compressor can adhere to the impeller, which will result in unwanted vibrations. Vibrations can result in increased maintenance requirements [33].

The particles that do not adhere to the impeller will move further downstream in the system. The intercoolers, aftercoolers, and the cooling and drying plant are downstream from the compressors. Particles that reach these components will cause build-up resulting in

inefficient operation. In the worst case of improper maintenance, it could cause clogging of the coolers [34].

The compressors are the components that increase the pressure of the air. As discussed, compressors operate at their best with clean air. It is important to select the appropriate compressor/s according to the application thereof. For small-scale operations, reciprocating compressors are usually sufficient. In cases where large volumes of compressed air are required, centrifugal compressors are preferred.

Since air is heated when compressed, intercoolers are required for multistage compressors. The intercooler reduces the temperature of the air before it enters the next stage of compression. An intercooler needs to be matched to a compressor for best results. The number of intercoolers depends on the number of stages that the compressors have.

Depending on the application, an aftercooler may also be required. For an application such as a blast furnace, the air is not cooled since the blast furnace requires high temperature air. However, when supplying instruments or secondary compressors for further compression, the air needs to be cooled first. The aftercooler is also selected according to compressor specifications.

The cooling towers mentioned in Table 1 are for cooling the compressor machine and motor. They are also used for the intercoolers, aftercoolers and cooling plant heat exchanger. A simplified layout of the cooling system is given in Figure 16.

The layout given is for a typical compressor plant. Each compressor plant is different and will, therefore, have a unique layout. The specific requirements of a compressor plant will determine the following:

- Number of cooling towers (indicated by CT)
- Type and number of heat exchanger/s (indicated by HX)
- Number of compressors (indicated by C)
- Intercoolers (indicated by ICs) and aftercoolers (indicated by AC)
- Cooling and drying plant heat exchanger
- Other components such as pumps (not shown in Figure 16)

To prevent overheating of the machines, demineralised water (indicated by “demin. water”) is fed from a plate heat exchanger through cooling ports in the compressor. After circulating

through the compressor, the water is returned to the heat exchanger to be cooled. A similar path is followed for the intercoolers and aftercoolers.

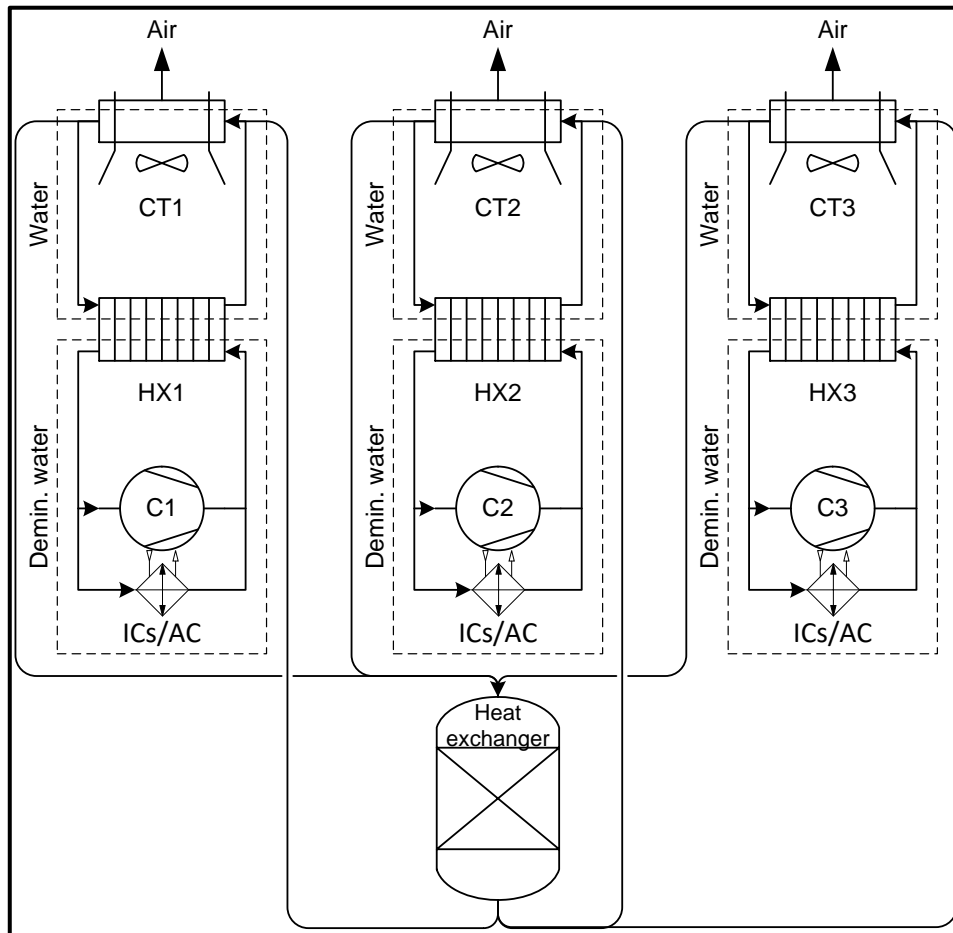


Figure 16: Compressed air plant cooling layout

On the other side of the plate heat exchanger, cooled water is used to cool the demineralised water. After the heat exchanger, the water is fed through a fan-operated cooling tower to cool the warm water. The cold water is stored in a dam or cool-water sump before it is fed to the heat exchanger. The cooled water is also used for the cooling and drying plant.

A cooling and drying plant is used to cool and dry the instrument air. This results in good quality air that will reduce wear and maintenance requirements of the instruments. The cold water from the cool-water sump is sprayed into a direct contact air cooler (DCAC) to rapidly cool the air. The result is cold but moist air. The moist air is dried in a dryer using desiccant.

Distribution system

The distribution system is the connection between the supplier and consumer of compressed air. The compressed air generated by the compressed air plant is supplied to the different

consumers using piping networks. The piping network is designed according to the specific system requirements.

In most large-scale systems, a compressed air ring approach is followed. Since the air is supplied from two sides, it reduces the velocity and pressure drop [21]. This is also an ideal approach for a system that has numerous consumers at different points. Each consumer is simply connected to the ring main. With the strategic placing of shut-off valves, certain sections can be closed without disturbing the supply in other sections.

A simplified layout of the compressed air ring configuration is shown in Figure 17. With this configuration, the same pressure is delivered to all the consumers. It can be seen in the figure that one of the consumers (Consumer 8) is fed from a reducing valve because only the one specific plant requires a lower pressure.

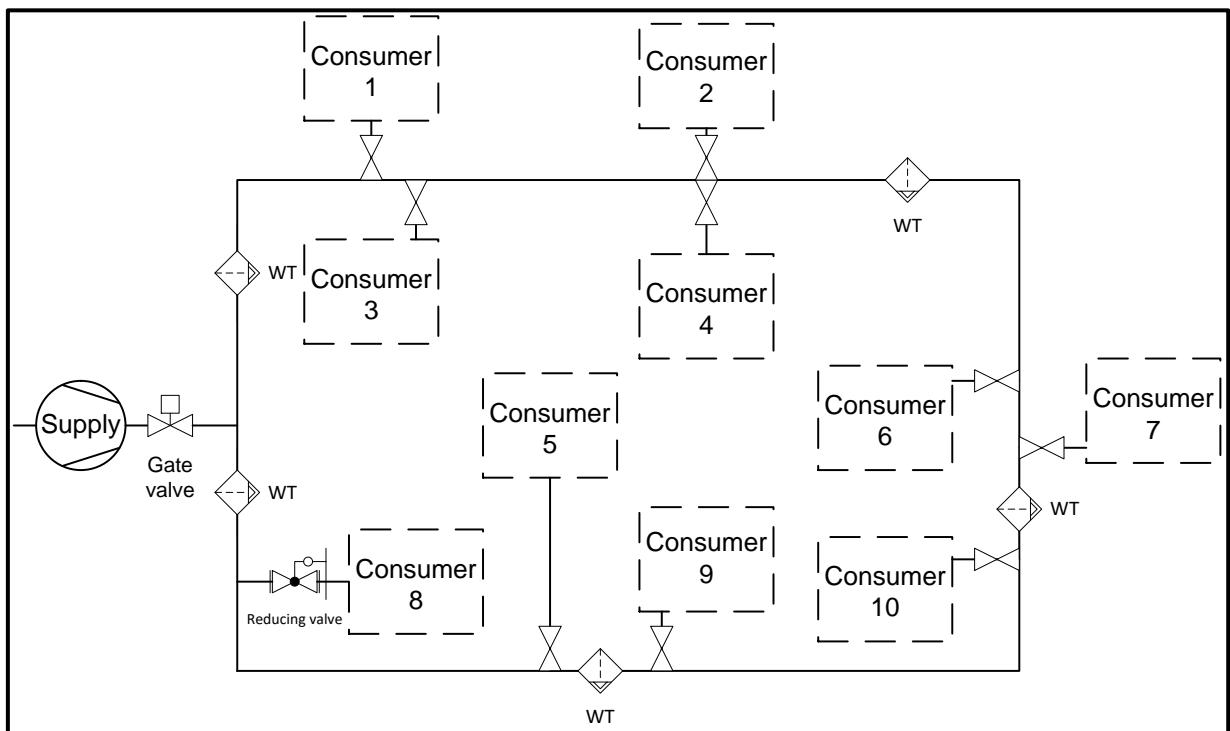


Figure 17: Layout of compressed air ring distribution

In certain cases, it may be the best option to supply certain consumers with a single compressor. The major reason being that there is only a small number of components requiring a pressure that is different from the other components in the system. Therefore, the ring main can be kept at the minimum pressure required for the majority of components. The components that require a different pressure can then be supplied by a single standing compressor. This will result in energy savings.

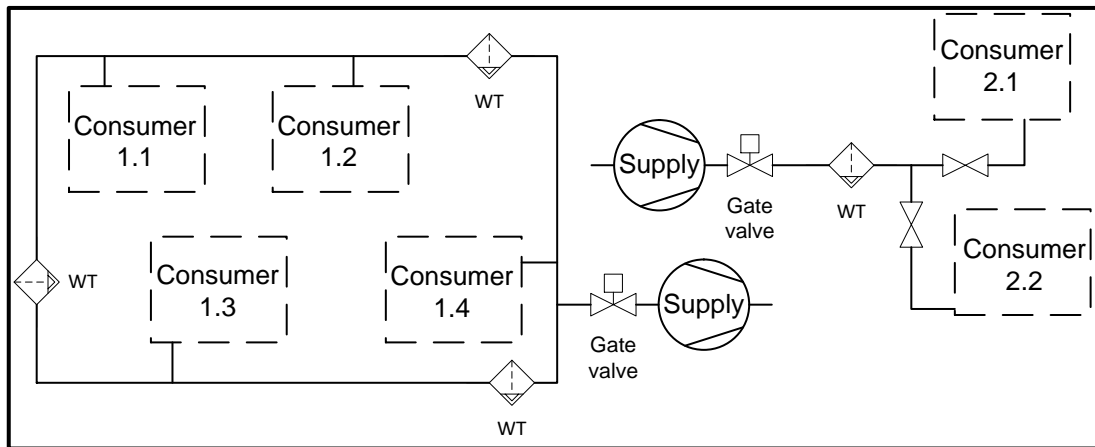


Figure 18: Compressed air ring distribution combined with a single compressor supply

For example, if it is found that Consumer 1 and Consumer 2 require a pressure that differs from the ring main, the strategy in Figure 18 can be used. Consumer 1 has a large number of subconsumers and, therefore, the ring supply strategy can be used. However, the compressed air is supplied by a compressor separate from the main ring supply. Consumer 2 only has two sub consumers. Thus, it can be supplied directly from a separate compressor.

As in the case of certain components requiring a higher pressure than the ring main, there are also components that require a lower pressure. As mentioned before, pressure regulators can be used to reduce the pressure to the required point. This is not energy efficient; therefore, replacing the components with higher pressure-rated components should be considered [21].

Figure 17 and Figure 18 also show water traps (indicated as WT) at various points on the distribution system. The water traps are installed to remove most of the remaining condensate in the pipes. The drying plant removes most of the moisture from the air. Due to valves and other components, there are changes in the properties of the air. The expansion of air after a partially open valve results in a certain amount of condensate forming. The condensate that formed is then removed by the water trap.

The storage/surge tanks are used as a damper for any sudden changes in the system. When the demand suddenly increases, the pressure will drop due to the time required for the compressor to react to the change. The storage/surge tanks reduce the pressure drop by supplying the need from the stored capacity. A large tank can be installed at the compressor plant or small tanks can be installed at each consumer.

The final component of the distribution system is pressure regulators. The compressor plant also has pressure regulators in the form of relief valves. These valves are used to prevent

overpressurising the system. The distribution line has pressure regulators to ensure that the correct pressure is delivered to the consumer.

Application equipment

Application equipment can be seen as the components used by the end consumers. A wide variety of components are available with only a few mentioned in Table 1. Actuators are the most commonly used component. They are used for controlling other components, which are used for manufacturing, opening and closing valves, and operating machine switches.

Air nozzles are mostly used to generate a concentrated high velocity air stream. This is used to clean surfaces by blowing off the dirt. This method of cleaning is widely used in the steelmaking industry for the rolling processes. To avoid imperfections, dirt is blown off the sheet of metal before it is rolled. Compressed air nozzles can also be used to regulate the thickness of galvanising and paint applied during mass production.

2.4 COMMONLY USED COMPRESSORS

There is a range of compressors available for the different applications of compressed air. Some compressors are designed to compress gases rather than air. Each application has specific requirements in terms of flow, pressure and temperature. An additional factor that should play an important role in compressor selection is energy efficiency. The basic types of compressor are [35]:

- Reciprocating
- Rotary
- Centrifugal
- Axial

Figure 19 shows a graph with the typical operating range for each type of compressor. This graph can be used to determine which compressor is best suited for an application based on flow and pressure requirements.

In this section, each of the compressor types will be discussed together with a typical application of each. At least one compressor from each group listed above can be found on a steel production plant. In the final part of this section, a centrifugal compressor will be discussed in more detail. From the discussion it will become clear why this type of compressor is used for supplying compressed air to blast furnaces.

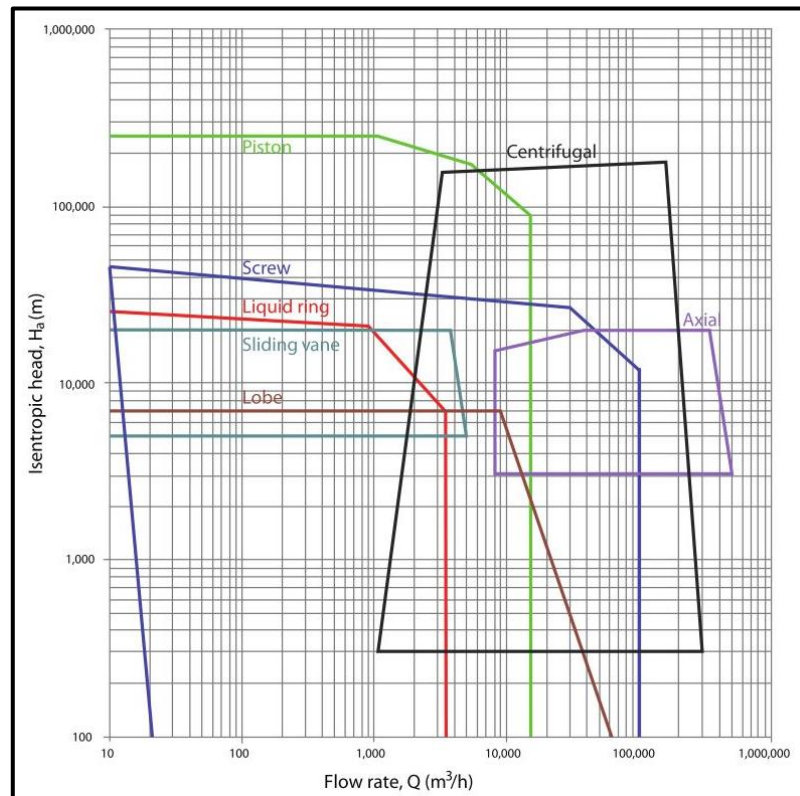


Figure 19: Operating ranges for different types of compressor [35]

2.4.1 Operating principle and application of different compressors

Except for the types previously listed, other types of compressor are also available. There are more specialised compressors for specific applications. The working principle is similar with adjustments made for the purpose of system design. Each of the compressor types listed previously will be discussed separately with an application of each.

Reciprocating

A reciprocating compressor is of the positive displacement type. It consists of a piston moving up and down inside a cylinder to compress air. It also has valves to regulate the direction of flow at different points of operation and relief valves to ensure safe operation. The reciprocating motion of the piston is made possible by a crankshaft driven by an electric motor (in most cases). A typical reciprocating compressor with a storage tank is shown in Figure 20.

It can be seen from Figure 19 that this type of compressor is able to deliver the highest possible delivery pressure. Several stages are used to achieve the maximum pressure. Due to the working principle, air is supplied in pulses. A storage tank can be used to eliminate

most of the pulsing. This type of reciprocating compressor is commonly used in refrigeration systems [35].



Figure 20: Typical reciprocating compressor with storage tank⁴

A more energy efficient type of reciprocating compressor is the moving-magnet linear compressor. Its motor efficiency is 74% at the design point, which can be improved to 86% with further development. A sectional view of this compressor is shown in Figure 21. The largest advantage is the reduction in frictional losses by eliminating the need for a crankshaft and bearings [36].

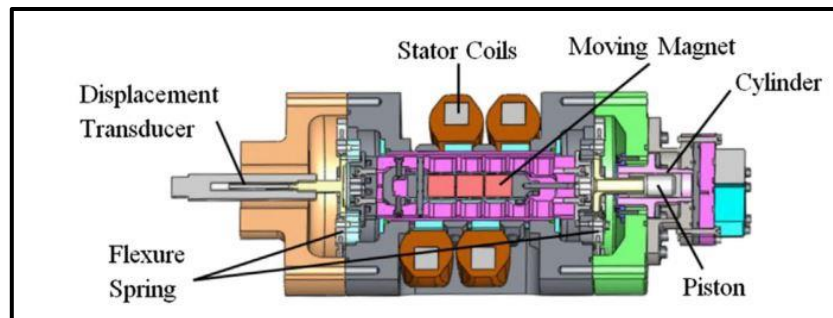


Figure 21: Sectional view of a moving-magnet linear compressor [36]

This compressor has a linear motor that slides a magnet forwards and backwards. This motion drives a piston inside a cylinder, resulting in compressed air being delivered. Due to the advantages and its compact size, this type of compressor is ideal for cooling of electronic equipment [36].

Rotary

Rotary compressors (as shown in Figure 19) is a group of compressors consisting of screw (Figure 22a), sliding vane (Figure 22b) and lobe compressors (Figure 22c). From Figure 19 it can be seen that this type of compressor does not have such a high header pressure as

⁴ APPL, Air Power Products Limited, [Online]. Available: <http://www.airpowerproducts.com/CatalogImages/CategoryImages/lubricated-reciprocating-air-compressors.jpg>. [Accessed 27 08 2016].

reciprocating compressors. Some of these compressors are, however, able to deliver a higher flow.

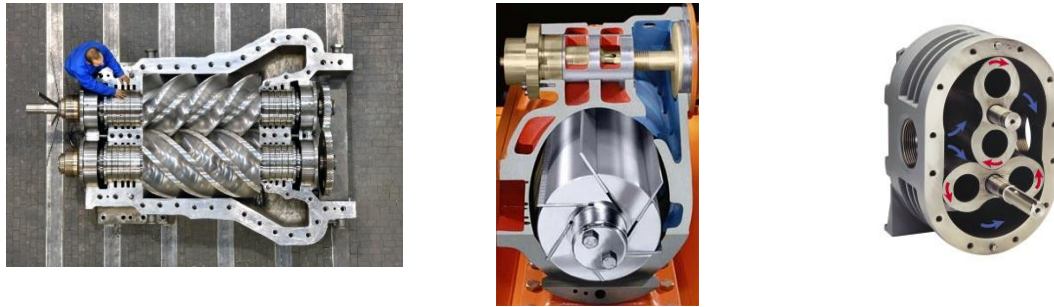
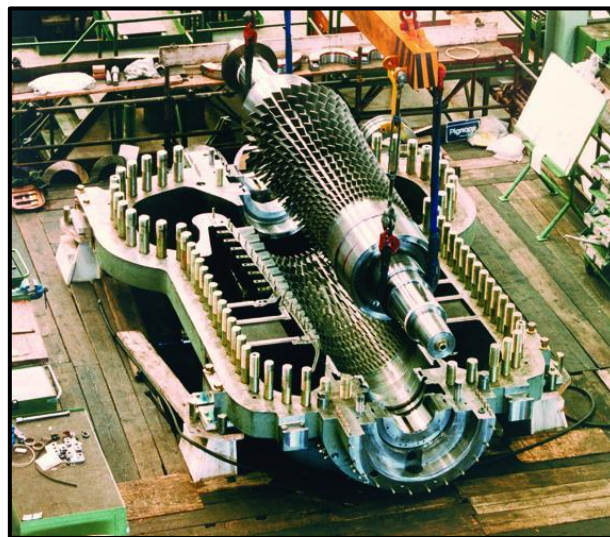
a) Screw⁵b) Sliding vane⁶c) Lobe⁷

Figure 22: Rotary compressor types

Axial

In Figure 19 it can be seen that this type of compressor is able to deliver the highest possible flow rate of the different types of compressor. Figure 23 shows a typical axial compressor with the housing removed. The rotor blades can be seen on the rotor shaft and the stator blades in the housing.

Figure 23: Axial compressor used for compressing air⁸

The rotor shaft rotates to compress air using the rotor blades. The stator vanes are installed to guide air through the several stages of the compressor. Inlet guide vanes are also installed

⁵ imgur, [Online]. Available: <http://i.imgur.com/Ayn1o4g.jpg>. [Accessed 03 09 2016].

⁶ Pneumofore, [Online]. Available: <http://www.pneumofore.com/rotary-vane/rotary-cutaway.jpg>. [Accessed 03 09 2016].

⁷ Unimac, [Online]. Available: <http://www.unimacpl.com/wp-content/uploads/2013/01/sutorbilt-cutaway-300x270.jpg>. [Accessed 03 09 2016].

⁸ Unimac, [Online]. Available: <http://www.unimacpl.com/wp-content/uploads/2013/01/sutorbilt-cutaway-300x270.jpg>. [Accessed 03 09 2016].

before the first stage. The amount of flow delivered by the compressor can be controlled by adjusting the inlet guide vanes.

This type of compressor is used in industries where large volumes of air are required. Some blast furnaces are supplied with compressed air by this type of compressor. It is also commonly used in airplane engines. An airplane engine has a turbine downstream from the compressor that supplies rotational movement to the compressor.

Centrifugal

In the large-scale operations of industry, centrifugal compressors are driven by electric motors. The motor shaft rotates an impeller that compresses the air. The air is sucked in at the centre of the impeller. Due to the rotation and blade design, air is compressed and leaves the compressor at the outer ring of the housing [37]. Figure 24 shows a typical centrifugal compressor used in industry.

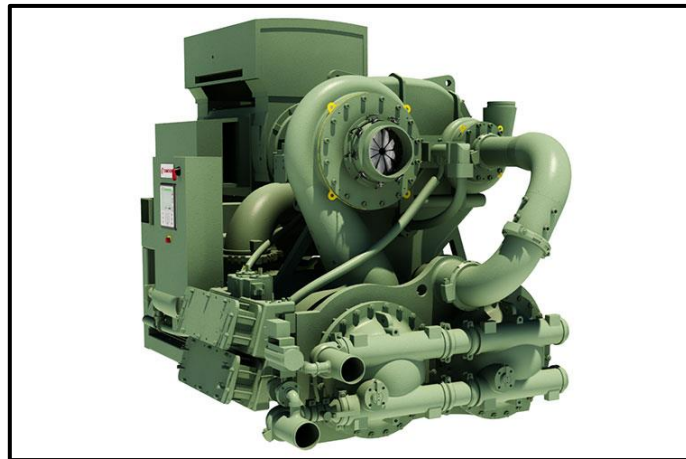


Figure 24: Typical centrifugal compressor used in industry⁹

A centrifugal compressor is most commonly known as a “turbocharger” in the automotive industry. A turbocharger is a relatively small component that increases the performance of an automotive vehicle. It has a turbine which operates on engine exhaust gases, instead of an electrical motor, that supplies the rotation for the compressor [38].

Centrifugal compressors have a wide range of applications, especially in the oil and gas industry. This is due to the high efficiency of this type of compressor as well as the wide range of flow that can be achieved [22]. For the same reason, they are also used in the ironmaking industry. This will be discussed in more detail in Section 2.4.2.

⁹ Compressedairducation, [Online]. Available: <http://compressedairducation.com/wp-content/uploads/2015/06/Primary-Compressor-Photo.jpg>. [Accessed 25 06 2016].

2.4.2 Centrifugal compressors

Most of the focus in this study will be placed on centrifugal compressors. The most basic centrifugal compressor consists of a single stage. If a single-stage compressor is unable to supply the required pressure, there are two possible solutions. The first is to add another compressor in series to further increase the pressure. The second option is a multistage compressor. The two solutions are similar in principle, but the preferred method will be determined by system and space limitations.

Figure 25 shows a multistage centrifugal compressor with the casing removed. Depending on the application, several stages may be used to increase the final pressure. Between each of the stages there is an intercooler to cool the air before it is further compressed. In certain applications, a certain amount of flow is tapped off at each stage. The result is a single multistage compressor providing air at different pressures for different applications.

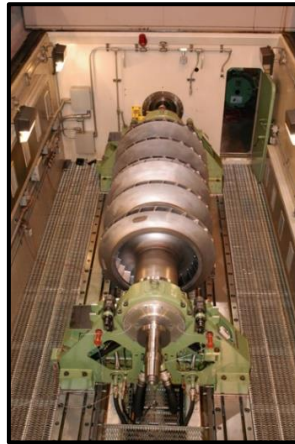


Figure 25: Multistage centrifugal compressor¹⁰

The multistage compressor approach is a more compact solution than two compressors in series. Adding another compressor also requires installing another electric motor and other auxiliaries. The available space places a constraint on proceeding with this strategy. However, due to the costs involved in replacing a single-stage compressor, the additional compressor method may be preferred.

It has been said that centrifugal compressors are energy efficient. Before deciding on a strategy for an increase in delivery pressure, the energy efficiency needs to be considered. The initial cost of installation may be higher, but due to the higher energy efficiency, a large

¹⁰ Sulzer, [Online]. Available: https://www.sulzer.com/de/-/media/Media/Images/ProductsAndServices/TurbomachineryServices/Equipment_Supported/TS_12_2_Compressor_rotor_as_HSB_DSC_0011.JPG?bc=ffffff&mw=690. [Accessed 25 06 2016].

cost saving can be achieved in the long term. The multistage compressor is commonly used due to the high pressure ratio, efficiency and stable operation [22].

There are different compressor control strategies to supply the needed demand. The two most basic methods are guide vane control and speed control. In the case of a system consisting of more than one compressor, different control strategies exist. The most basic strategies for this type of system are on/off control and load/unload control. These strategies will be discussed in more detail in Section 2.5, which focuses on compressed air energy savings.

2.5 COMPRESSED AIR ENERGY SAVING STRATEGIES

Some of the earliest examples of energy saving strategies on industrial systems date as far back as the early 1970s. Energy management became necessary to reduce consumption. The basis of this innovation was the availability of accurate data. From this a better understanding of usage profiles and areas that require attention could be gained [39].

The life expectancy of energy sources increased due to reduced energy consumption, thus resulting in more sustainable operation. Also due to the decreased energy bills, funding was available for more energy saving strategies. The final result is a more energy efficient process that increases profits [39].

A compressed air system is an important component in the mining industry. Due to this, the compressed air energy saving strategies implemented in the mining industry will be discussed in this section. Additional to this, some general energy saving strategies that could be implemented on compressors will also be discussed. This gives a good overview of the possible strategies that can be implemented in the ironmaking industry.

Compressed air is one of the most expensive utilities [21]. Several energy saving strategies have been developed to reduce the cost of compressed air. The different strategies can be divided into two major groups [40]:

- Demand-side savings
- Supply-side savings

In this section, different strategies from each group will be discussed. The expected energy savings from previous investigations will be given to determine the impact of the specific strategy.

2.5.1 Demand-side savings

Demand-side savings can be achieved by making the necessary changes at the end user or on the path to the end user. The subsections that follow give some of the reasons for energy inefficiencies on the demand side of a compressed air system [40]. A short discussion of each is given with the effect each will have on energy savings if it is corrected.

Compressed air leakages

A compressed air system consists of a large number of components. Each of these components has potential for energy loss in the form of flow or pressure loss [17]. Besides this, the connection between the components creates an opportunity for leaks to form. The majority of these leaks occur at the flange connections, valve systems, hoses, equipment connected to the system, and many more [18].

The most common reason for compressed air energy inefficiency is air leaks. On a typical system, approximately 15% to 50% of compressed air produced is wasted through leaks. The energy saving from repairing leaks is determined by the specific system under consideration. In general, an energy saving as high as 20% can be achieved [21].

It is clear that leak repair is a simple method for achieving a significant amount of energy savings. There is a wide range of repair methods available. One common method used is installing a repair clamp over the leak. A repair clamp, as shown in Figure 26, blocks the flow of air through the leak and can be installed while the system is in operation.



Figure 26: Air leak repair clamp¹¹

It is important to continue with proper system maintenance after repairing all the leaks. A maintenance schedule is needed to monitor the presence of any air leaks. Any new leaks

¹¹ Direct Industry, [Online]. Available: http://img.directindustry.com/images_di/photo-m2/69970-7379273.jpg. [Accessed 03 09 2016].

need to be repaired as soon as possible. This strategy requires considerable time to find and repair leaks, but is one of the cheapest methods for achieving energy savings [41].

Inappropriate use

It has become clear so far that compressed air generation is expensive and not very energy efficient. The end user is responsible for a large portion of the energy inefficiency. This is due to inappropriate and wasteful use [42].

There are a variety of energy efficient components available to be used in manufacturing. Due to the initial cost and lack of awareness, alternative equipment is used. Instead of using a specially designed nozzle, an open-ended hose may be used instead. This may be a health hazard depending on the pressure of the air used. An open-ended pipe also consumes more air than a properly designed nozzle would [17].

In many cases, compressed air is also used in applications for which it has not been intended. Some common examples are cleaning and drying of surfaces as well as cooling. Compressed air is expensive and should, therefore, not be used for these purposes. It has been found that a vacuum cleaner for cleaning and a fan for cooling are more energy efficient [21].

The major reason for inappropriate use is due to the misperception that compressed air is inexpensive [18]. By making the end user aware of the cost of compressed air, this perception can be changed. It requires minimal effort and a change of mind to achieve the necessary savings. The approximate energy saving that can be achieved by eliminating inappropriate use is 40% [21]. However, to achieve such a large saving system audits and monitoring is required, which may be expensive.

Pressure minimisation

The higher the pressure that a compressed air system supplies, the higher the costs to generate the air [21]. The compressor delivery pressure needs to be determined by the pressure required for the application equipment. The application equipment should be selected to minimise the pressure without reducing effectiveness.

Manufacturers of compressed air systems recommend that 25–30% more capacity be installed as a factor of safety. This oversupply is to compensate for all the unknown losses that exist throughout the system [18]. When oversizing a compressed air system, it also decreases the energy efficiency over the system's lifetime. Therefore, the system should be designed with a minimum factor of safety [21].

The pressure of a compressed air system should be close to the minimum required by the end user. Energy consumed rapidly increases with an increase in pressure. On average, a reduction of 100 kPa in system pressure can result in an energy cost reduction of 15% [21].

Distribution inefficiencies

Most manufacturing plants are built with a centralised compressed air system. This system supplies air to as many consumers as possible [18]. As mentioned in Section 2.3, some applications have specific needs. Provision is made for these applications as discussed in Section 2.3.

A study has been done on the ideal location of a compressed air plant. In this study, it was found that the plant should be located closest to the largest consumer. It should also be located to minimise the amount of energy lost due to the distribution of the air. By optimising the location of the compressed air plant, an average energy saving of 11% could be achieved. Also found in the study was that compressed air locations are chosen based on available space. Although this is not energy efficient, options are limited in an already established production plant [18].

In general, compressed air ring distribution networks are used. This is since the air can reach the consumers from two sides. The result is the same amount of volume delivered at a lower velocity. A lower velocity in the pipes results in a smaller pressure loss. Another advantage of a ring feed system is that a certain section can be closed for maintenance without disturbing the consumers [21].

When designing the compressed air distribution network, the losses caused by components need to be considered. It is important to keep the length of pipes required to a minimum. Where possible, large pipes need to be installed to limit the amount of pressure lost. Another component that causes a significant pressure loss is an elbow. Elbows should be avoided if possible. A properly designed compressed air network could make the system 12% more energy efficient [21].

Peak demand management

Peak demand refers to the time at which the electricity demand is the highest. This could be due to the production process, or several consumers having a high demand at the same time. When comparing the peak demand with the average demand, a power load factor can be determined. This is simply the ratio between the peak and average power demand [39].

It is favourable to keep the power load factor as high as possible. This is especially the case for South African industries using the Eskom's Time of Use tariff structure. A high load factor indicates that the load is spread evenly throughout the day. In South Africa, the aim is to reduce the consumption in peak periods. The result is significant cost savings due to the high cost of electricity in peak periods [39].

There are different methods for managing the peak time demand. A common method is load shifting. The electricity usage profiles are studied after which changes are made to optimise the profile. By spreading the load, a flat usage profile can be obtained [43].

Another method that requires the availability of funds and the installation of equipment is compressed air energy storage. A container is filled with compressed air during off-peak periods. During peak periods the stored air can be used to drive a turbine for electricity generation [19]. This is a simple concept that reduces electricity costs. Figure 27 shows the process layout of a compressed air energy storage facility.

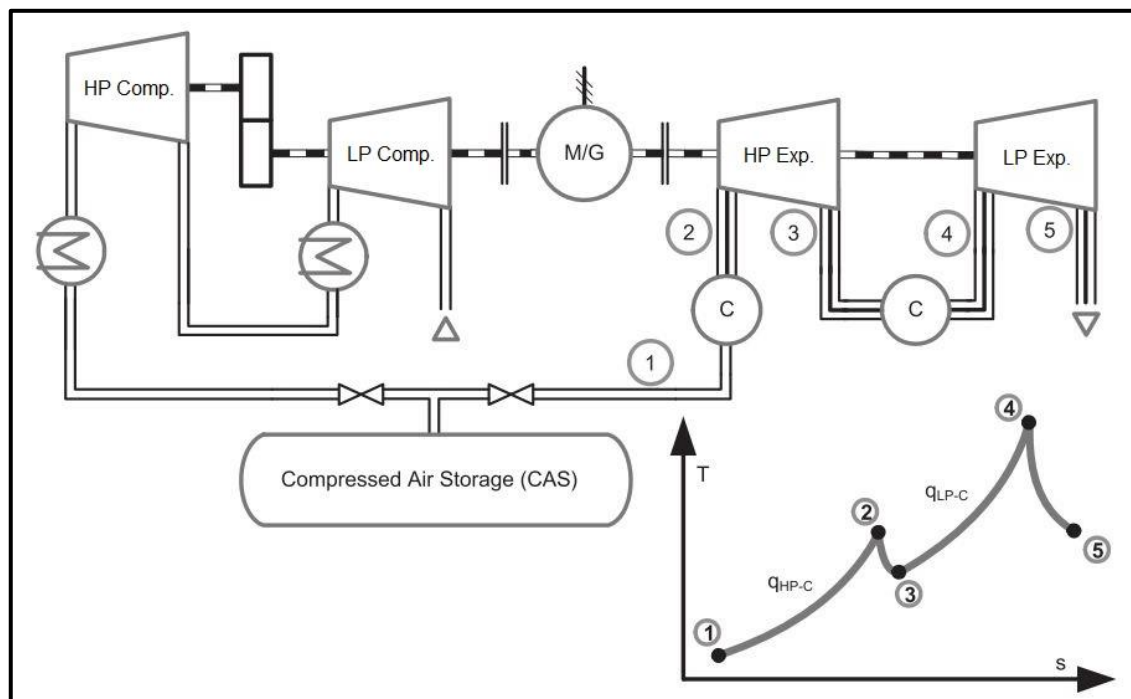


Figure 27: Compressed air energy storage process diagram [44]

In the bottom-right of Figure 27 is the temperature entropy diagram for the process. The air is heated through combustion between Point 1 and Point 2. After this, it is expanded through a high pressure turbine. Before the air is further expanded in a low pressure turbine, it travels through a reheater to increase the temperature of the air. The motor/generator (indicated by M/G) is located between the compressors and turbines. Depending on the mode of operation, the clutches on each side will be engaged or disengaged [44].

2.5.2 Supply-side savings

In this section, attention will be given to the supply side of a compressed air system. Several studies were performed before a suitable and simple method for characterising a compressor was found. From the models developed, a specific compressor can be optimised to be more energy efficient. There are several methods of optimisation, but only a few will be discussed here.

In order to better understand the operation of compressors, compressor models can be built. The models can be based on theory or experiments. Theoretical models are based on laws of mass, energy and momentum conservation. The problem with theoretical modelling is the complexity thereof and the computational requirements [45].

In a diagnostic environment where the aim is improving performance based on tests, experimental models are more suitable. This type of modelling is commonly represented by a compressor performance map. Empirical models of compressor performance are the mathematical interpretation of compressor performance maps. A centrifugal compressor specifically can be characterised by a map with pressure ratio and volume flow used as coordinates [45]. An example of a compressor map is shown in Figure 28.

The left-hand boundary on the map is known as the surge line. At this point, the airflow through the compressor becomes too low for the pressure ratio. The result is that the air can no longer adhere to the suction side of the blades, causing an interruption in the discharge. When operating on the left-hand side of the surge line, a large amount of flow instability is caused [45].

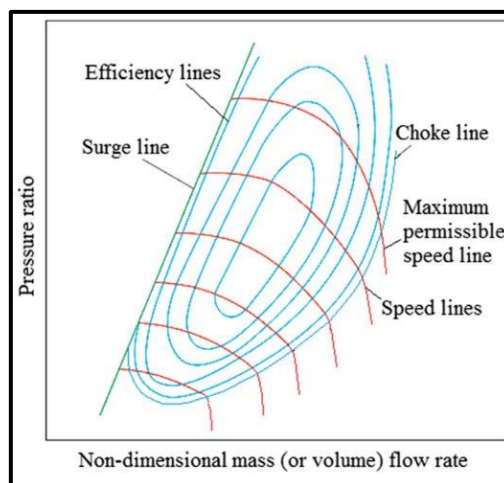


Figure 28: Compressor performance map [45]

The right-hand boundary is known as the choke line. This is a limitation caused by the cross section at the compressor inlet. When the volume flow increases, the velocity at the inlet also increases due to the area being constant. As the velocity approaches sonic velocity, the inlet has a choking effect. The compressor inlet is unable to supply the required volume flow [45].

Compressor operation and control

Controlling and operating compressors are of the most important factors in compressed air systems. Each system will have a different control based on the system layout, number of compressors and consumer requirements. With a compressed air system requiring only one compressor, the control is relatively simple – the compressor is only operated when required. This is the most energy efficient control [39].

With a system consisting of more than one compressor, the control becomes more complex. It is important that compressors are correctly sized since an oversized compressor consumes more electricity than a properly sized compressor. The result is higher annual costs to operate the oversized compressor [17].

Another important consideration is operating the combination of compressors in the most efficient way. Only one compressor should handle the variation in load while the other compressors operate near maximum to supply the baseload. The most efficient compressors should be used to meet most of the demand [17]. Figure 29 shows an example of this strategy using variable speed drives (VSDs).

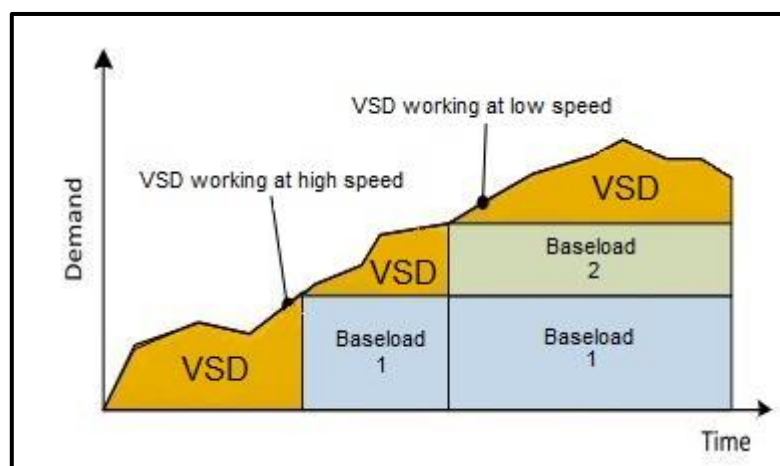


Figure 29: Compressor control with VSDs (Adapted from [17])

In Figure 29 it can be seen that initially only one compressor is operated with a VSD. As time passes the load varies, but due to the VSD the compressor is able to meet the demand. At a certain point, the demand becomes too high for a single compressor. At this stage, the

first compressor supplies the baseload with the second compressor operating on a VSD. It can be seen that at a later stage the first two compressor supply the baseload with a third compressor on a VSD. When the load decreases, the opposite procedure from the above is followed until only one compressor is required again [17].

There are other methods also for controlling the amount of compressed air the compressor is supplying. Figure 30 compares the three most common types of supply control. From the comparison it can be seen that VSDs are the most energy efficient. VSDs are, however, expensive, especially those used in industry that need to operate in the megawatt range. An alternative is inlet guide vane control. This method is less efficient than VSDs, but already an improvement on a throttle valve [46].

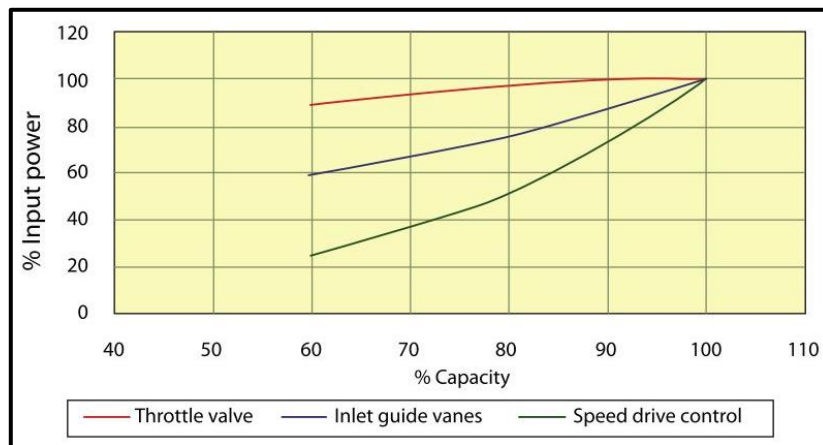


Figure 30: Compressor control comparison [46]

Environmental control

A factor that is not often considered in compressor operation is the environmental impact. It is advised to use cooler outside air to improve the efficiency of the compressors. A reduction of 3 °C in the inlet air temperature would result in a 1% saving in consumption. This is due to the higher density of the air entering the compressor [21].

It is also important to ensure that good quality air is provided to the compressors. The atmospheric air at a steel production facility is known to be very dirty. This is due to a large amount of dust, presence of smoke and coal particles, and several other hazardous gases. Before the air enters the compressor, it should first pass through a quality filtering system.

The filtering system should clean the air properly without having a large pressure drop over the filter. When the pressure drop is high, it causes the compressor to operate inefficiently due to choking. However, any dust particles that reach the compressor build up on the rotor. The build-up results in machine vibrations and if left unattended could cause major damages.

System auxiliary equipment

From the previous section it was found that a compressed air plant requires a large amount of auxiliary equipment. This equipment includes intercoolers and aftercoolers, air dryers, water traps, and storage tanks. Components such as the coolers and dryers reduce pressure before the air is delivered to the end user.

System auxiliary equipment should be selected to maximise the efficiency and minimise the pressure drop caused by the component. Any pressure drop at the supply side is lost energy that could have been provided to the end user.

A DCAC is commonly used due to the low pressure drop associated with it. However, due to an increase in moisture, a dryer needs to be used with a DCAC. Some compressed air systems have refrigeration systems for the purpose of cooling and drying. The pressure drop over these systems are, however, significantly higher.

New technology

For existing systems using old equipment, it may be feasible to replace the equipment with new technology. The most basic type is replacing a compressor motor with a new energy efficient motor. Modern compressor motors are approximately 7% more energy efficient [21]. Considering the cost of operating a compressed air plant, this strategy will be feasible in the long term.

2.6 LITERATURE REVIEW

In this section a review of previous studies will be done. Energy savings in general and energy on compressed air systems will be considered. This review will aid in the development of an energy saving strategy for this study.

2.6.1 Energy benchmarking

C Cilliers, 2016 [47]

The study by Cilliers developed a benchmarking model for energy use in mining. In the study it was found that there are five major electricity consumers in mining that need to operate continuously. These consumers, of which compressed air is one, are required to ensure optimum output. The study was specifically aimed at benchmarking electrical energy consumption of the five largest consumers.

The benchmarking model was used to determine the energy consumption for average and best practice situations of the five consumers. A method to prioritise energy efficiency strategies was also realised. The benchmarking model was verified using actual energy efficiency data. Validation through case study was also done. The model was found to be accurate in prioritising energy efficiency strategies.

From the study by Cilliers it was found that compressed air is one of the five highest consumers of electrical energy in the mining industry. The study was not only aimed at determining the largest consumers, but also at ranking energy efficiency strategies. It had to be determined which strategies would have the largest impact on energy savings before developing a strategy.

Conclusion

From the study conducted by Cilliers it was determined that compressed air systems are one of the largest energy consumers in industry. As recommended, the different energy saving strategies and the possible impact of each were identified. The number of strategies that could be implemented for the purpose of this study needs to be determined from system and operational constraints.

S.G.J. van Niekerk, 2016 [48]

Van Niekerk conducted a study on “Quantification of energy consumption and production drivers in steel manufacturing plants”. In the study it was found that steel production plants are large, integrated and complex energy consumers. From research it was found that current quantification techniques use inaccurate data. This is mainly due to disorganised, decentralised and unverifiable data sources.

The study was done due to the South African government introducing regulations with the aim of monitoring and reducing carbon emissions. For these regulations, accurate and verifiable data of energy consumption and production drivers is required. Energy efficient tax incentives are given to industries which improve on energy efficiency.

Conclusion

Van Niekerk’s study highlighted the importance of accurate and verifiable data. In this study, an effort was made to ensure that all data used was accurate and verifiable. All data used in this study was measured with an energy management system. Additional to this, the data

was also measured on-site and stored on a historical database. In the case that one data source fails, another can be used.

2.6.2 Compressed air energy

C.J.R. Kriel, 2014 [49]

In the study conducted by Kriel it was found that the mining and industrial sector of South Africa consumed approximately 43% of total electricity generated in 2012. From the electricity generated, 10% was used to produce compressed air. When reducing the electricity consumption of compressed air systems, it reduces the strain on the electricity network. It also reduces overall production costs, which increase profits.

There are several compressed air systems on which energy saving strategies were already implemented. However, it was found that not all of the implemented strategies were sustainable. Some of the main reasons for this was due to improper training, lack of maintenance and system changes. Energy saving potential through modernising of compressed air systems was considered.

As a starting point, data was collected from mines where energy saving strategies have already been implemented. Using the data, a simulation was done to investigate the possibility of energy savings through modernising. The improvements that were found to be feasible were implemented and monitored for three months.

Conclusion

From the study by Kriel it has been determined that even on compressed air systems with energy savings already implemented, there was a possibility of more savings. The investigation process that was used, which included the data collection and simulation, will be considered in this study.

Due to the work done by Kriel, the sustainability of the strategy developed in this study is considered to be very important. The system has certain constraints, with no infrastructure changes being a requirement. With this in mind, a sustainable energy efficient strategy needs to be developed and implemented.

A significant improvement in energy efficiency can be seen through proper maintenance. Proper maintenance will also ensure sustainable operation of the compressed air system. Other strategies, such as supply and demand matching, are also sustainable solutions.

JH Marais, 2012 [50]

In 2012, Marais stated that the demand for electricity in South Africa has grown faster than the increase in generation. Commissioning new power stations is expensive and time consuming. An alternative to this is the DSM strategy. Energy saving strategies are implemented on the electricity demand side to decrease the consumption. This provides the necessary time required for the construction of new power plants. It is also a less expensive strategy.

Compressed air is a large consumer of electricity in the mining sector of South Africa. It is also known that there is a large amount of compressed air wastage on these systems. On a typical mine, the compressed air system consists of multiple compressors located at various locations. It was found that optimising a single compressor may not be the best solution. It may adversely affect other parts of the system.

The study by Marais focused on a new approach to simplify mine compressed air systems. In this approach, saving opportunities could be identified and the true impact of saving efforts assessed. In the end, a new implementation procedure was developed. The procedure was used to integrate different energy saving strategies and maximise the savings that could be achieved.

Conclusion

It is noted from Marais's study that the effect of an energy saving strategy on other system components has to be considered. Considering a single component in isolation will not result in maximum energy savings. An integrated approach needs to be followed to achieve maximum energy savings on the system as a whole.

In this study, the effect that the implemented strategy has on the system needs to be considered. For the purpose of this study, the entire system will not be optimised. However, it will be ensured that the system will be able to operate as usual after implementation of the strategy.

A large difference between mining and ironmaking is the layout of the compressed air system. In an ironmaking plant, all the compressors are located at the same point. The compressed air system also consists of several compressors of which most need to operate continuously. Due to the demand and infrastructure limitations, there is no potential for stopping and starting compressors during normal operation.

FW Schroeder, 2009 [51]

In 2008, the backlog of electricity supply in South Africa resulted in an energy shortage. Schroeder conducted a study on “Energy efficiency opportunities in mine compressed air systems”. He found that DSM is one of the most viable short-term solutions to address the backlog. This is due to the short implementation time and significantly lower price than constructing a power plant.

Various energy efficiency strategies that can be implemented on compressed air systems were investigated. Some of the strategies that were investigated included eliminating air leaks, optimising compressor selection and control, and minimising pressure drops. Based on several factors such as financial feasibility, sustainability and ease of implementation, the best strategies were identified.

Conclusion

The best energy efficient strategies were found to be:

- Controlling the system pressure optimally
- Minimising compressed air leaks
- Optimising control and selection of compressors

For this study, considering all requirements and constraints, the optimal control of system pressure may be the best strategy. This strategy could be implemented without any changes to infrastructure and minimal impact on system operation.

2.6.3 Conclusion of literature review

From the literature review several important factors for energy saving potential have been identified. The importance of the availability of reliable data and energy benchmarking was identified. It was also determined that compressed air systems is one of the largest electricity consumers in industry.

In Section 2.6.2, several studies on compressed air energy savings were considered. From these it was found that it is important to follow an integrated approach. By doing this, the impact that one component has on the other is considered. The entire system can then be optimised to maximise the energy saving.

Schroeder’s study identified some of the best compressor energy efficiency strategies. It was also noted from the study by Kriel that systems where energy efficient strategies have already been implemented, there is more potential through modernising.

All the compressed air studies considered were based on mining systems since extensive energy efficiency work has already been done on the mining sector. During the literature review no studies on the optimisation of blast furnace compressed air systems were found. There is, however, a large amount of research available on blast furnace optimisation.

Due to the shortage of research on compressed air in the ironmaking industry, the research from the mining sector was considered. The strategies identified will be adapted according to the requirements of the ironmaking sector.

2.7 SUMMARY

Background on the operation of a blast furnace was given in this chapter. The use of compressed air and the importance of a reliable supply have also been discussed. Compressed air systems in general were discussed to identify the components that most compressed air systems require. A more detailed discussion was given on different compressors – specifically centrifugal compressors.

The reason for focusing on centrifugal compressors is because they are commonly used in the ironmaking industry. This is due to their high efficiency and wide range of flow. Different energy saving strategies that can be implemented on compressors were also discussed. The possible impact that each have on energy efficiency was also given.

In the final part of this section a literature analysis was done. In this analysis the work done in previous studies was considered. The relevance to this study and how the previous work can be applied to this study were determined. Energy benchmarking and measurement techniques were considered first. Next, studies that focused on compressed air systems were considered.

In the next chapter the information from this chapter will be used to develop a methodology for implementing compressed air saving strategies in the ironmaking industry.

3 IMPLEMENTING AN ENERGY SAVING STRATEGY

3.1 PREAMBLE

It can be seen from Chapter 2 that the ironmaking process is complicated with various variables. It is important to properly monitor and control these variables to ensure efficient and stable operation. A methodology to implement a saving strategy on the compressed air system of a blast furnace will be developed in this section. This methodology is required since blast air lines are properly maintained. Therefore, the simple saving techniques such as leak repair cannot be used.

Figure 31 gives an overview of the methodology that needs to be followed for the implementation of a compressor energy saving strategy. This generic methodology can be used on any ironmaking plant to achieve compressed air energy savings. In the following subsections it will be applied to an actual system.

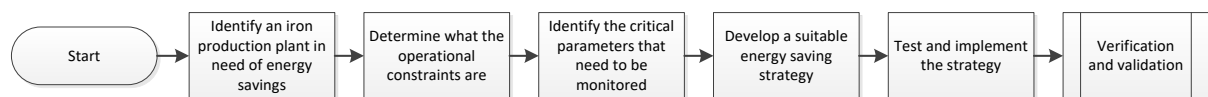


Figure 31: Generic methodology for implementing an energy saving strategy

The first step in the methodology is to identify an iron production plant that is in need of energy savings. Since ironmaking is an energy intensive process, almost any ironmaking plant can be used. The difficulty is in determining if an energy saving strategy can be implemented on the compressed air system. This will be determined by following the processes shown in Figure 31.

Once the plant agrees to investigate possible energy savings strategies, a system overview needs to be developed. This includes drawings of the plant layout, piping and instrumentation diagrams, and system specifications. When developing the system overview, the operational constraints also need to be identified. This may cause some limitations on the possible strategy that can be implemented.

The critical parameters can be identified from the system overview. These are the most important parameters that need to be closely monitored to ensure safe operation. The operating limits of the critical parameters need to be known. These parameters will be used when testing the strategy. The success of the test will be determined by the ability to operate within the operational limits.

With the system overview and critical parameters identified, the development of an energy saving strategy can be started. The theory of compressors needs to be considered when developing a specific strategy. The different strategies that were identified from literature need to be tested for suitability on the system under consideration. It needs to be determined if the given strategy will comply with operational constraints and not exceed the limits of the critical parameters.

After identifying a suitable strategy, the specific system parameters need to be considered in developing the final strategy. The final strategy that will be implemented is in the form of a control philosophy. After setting up the first revision of the control philosophy, it is presented to the system managers for implementation.

There are several steps required before final implementation. As shown in Figure 32, an iterative process is required when setting up the control philosophy. If the control philosophy is approved, a risk assessment, and a Hazard and Operability (HAZOP) study also need to be completed. The feedback from the managers and results of the HAZOP study are used to revise the control philosophy.

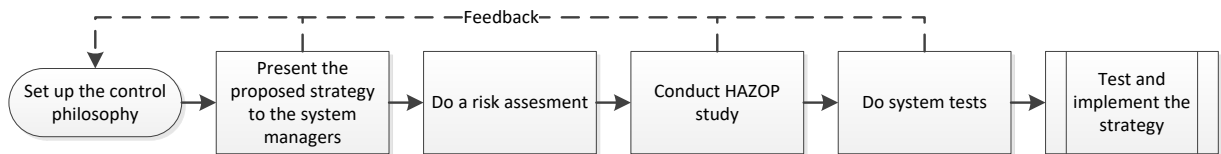


Figure 32: Iterative process flow for developing a control strategy

In the case of approval with a certain revision, some system tests can be performed. This is to ensure that valid assumptions were made in developing the strategy. Once the final control strategy has been approved, final testing and implementation of the strategy can be done.

Final testing requires the full implementation of the strategy while closely monitoring the system. The critical parameters need to be continuously monitored to ensure safe operation. During testing it can also be determined if the system stays within its operational limits. If all criteria of safe operation can be met, the strategy can be fully implemented.

The final step is verification and validation of the energy saving strategy. This will be discussed in Chapter 4. In this chapter the identified generic methodology will be applied to an actual system. This is to illustrate the process of implementing a compressed air energy saving strategy on an ironmaking plant and discuss some of the challenges that were experienced.

3.2 SYSTEM OVERVIEW AND OPERATIONAL CONSTRAINTS

The first step in implementing compressed air energy saving strategies on an iron production plant is to get an overview of the system. Included in this overview is the operational constraints of the given system. This section gives an overview of the actual system used for the case study.

The second part of this section contains the operational constraints. In this section the major constraints of the system are discussed. These constraints are important since they need to be considered when developing an energy saving strategy. It is also used to determine some of the critical parameters that need to be monitored for safe and sustainable operation.

3.2.1 System layout

Figure 33 shows a general layout of the system under consideration. The figure is a summary of the general system layout and the piping and instrumentation diagram. However, no instruments are indicated on the diagram; only the major components of the system. The major components as shown in Figure 33 are as follows:

- Low pressure (LP) compressors
- Supply valves
- Flow control stations
- Pressure control stations
- Snort valves
- Stoves
- Blast furnaces
- High pressure (HP) compressors and PCI compressors
- Cooling and drying plant

The items listed above are the major components that should be found on any ironmaking plant. The system configuration, number of each component and rating of each component will be different for each plant.

The primary purpose of LP compressors is supplying blast air to the blast furnaces. The supply of low pressure air to different points of demand is controlled by the supply valves. The amount of airflow delivered to each blast furnace is controlled with the flow control stations. To ensure that the line pressure does not exceed the maximum allowed by the blast furnace, a pressure control station is also installed. The last control mechanism is the snort valve.

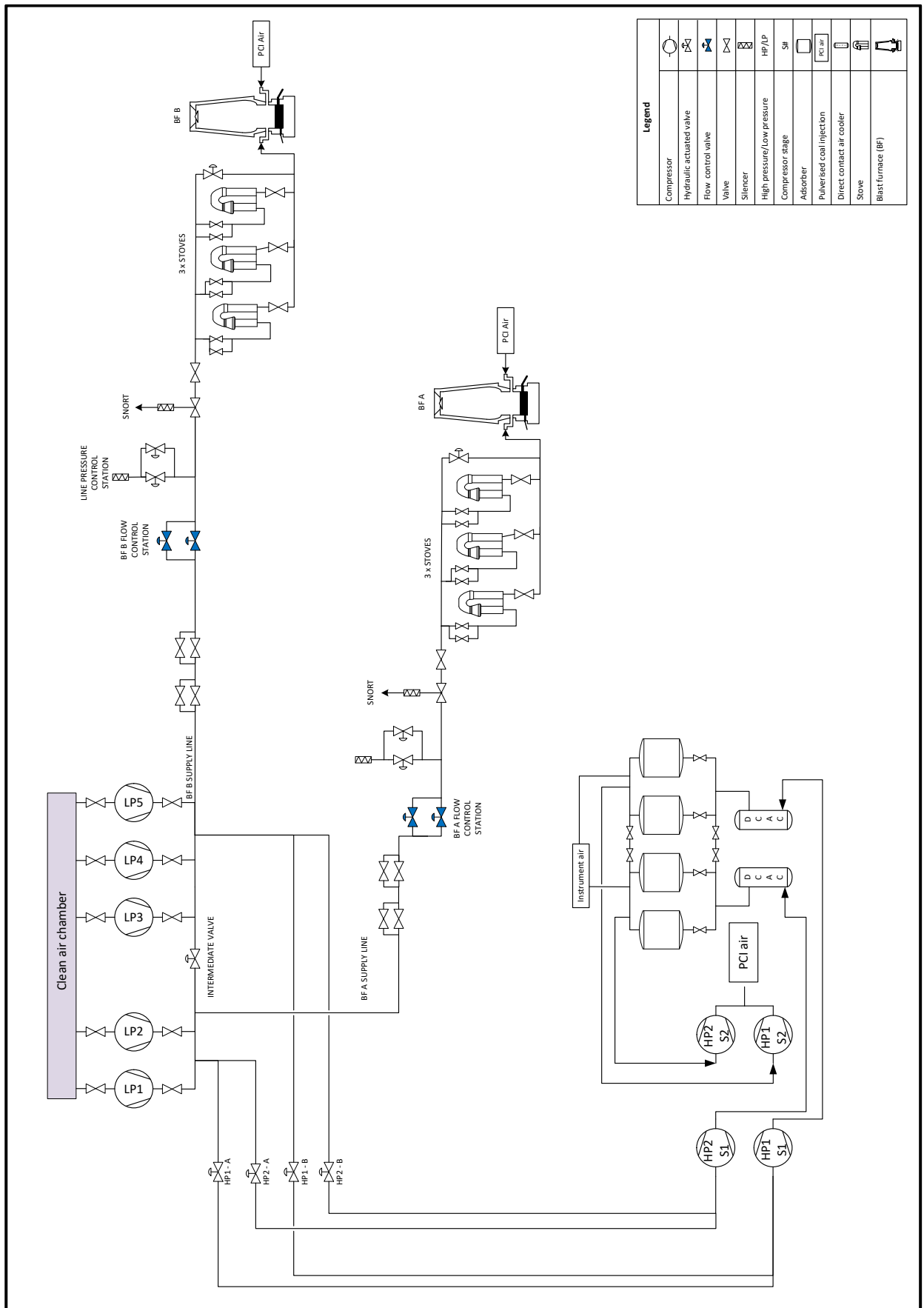


Figure 33: Layout of the compressed air system

The air supplied from the LP compressors is supplied to the stoves. Each blast furnace has three stoves to preheat the cold blast air. The working principle of the stoves was discussed in Section 2.2. After the stoves, the air is referred to as hot blast air. The hot blast air, which is at approximately 1 040 °C, is injected into the blast furnace through the tuyères.

The secondary purpose of the LP compressors on this specific system is supplying air to the HP compressors. The HP compressors further increase the pressure as required by instrumentation. The instrument air is cooled and dried in the cooling and drying plant. Most of the air is supplied to the works for instrumentation purposes. A certain portion of the air is returned to the remaining stages of the HP compressors for further compression. This high pressure air at approximately 1 250 kPa is used for PCI into the blast furnace.

Figure 33 and the above explanation provide a general overview of the system as a whole. At this point of the process, this is sufficient information. In the following section more detailed information will be required to identify the system constraints. This information is obtained from the system managers and system operators. The system layout can be updated to show the system constraints after they have been identified.

3.2.2 Operational constraints

In order to identify all the system constraints, it is important to communicate with the system managers as well as the operators. The managers will be able to supply information on critical system constraints due to certain limitations or changes to the system. The operators will be able to supply more detailed information on the day-to-day operational constraints.

Another important method for identifying operational constraints is through real-time monitoring and data logging. This will provide knowledge on the system capabilities and limitations. It will also provide additional insight into possible changes and the rate at which changes can be made.

This section gives and discusses the operational constraints that were identified on the specific system. For the specific system used for the case study it is required that there is no capital expenditure. Besides this, there are only four system constraints:

- LP compressor power and guide vane angle (GVA)
- HP compressors
- Blast furnace demand
- Rate of change

LP compressor power and GVA

In order to achieve higher flow rates, the LP compressor were upgraded with larger rotors. More electric power is required to operate the compressor at maximum load with the larger rotors installed. The original compressor motors were left unchanged and, therefore, precaution needs to be taken.

The result is that the compressors can only be operated between certain GVA ranges. This limits the amount of power required by the compressor motors. Therefore, the installed compressor motors are sufficient to supply the demand. Care should be taken to not operate outside the allowable GVA ranges.

HP compressors

Since the HP compressor inlet is fed from the LP compressors, any changes to the LP compressors will influence the HP compressors. Any intervention needs to consider this and ensure that the HP compressors are compensated for.

The HP compressors are used for instrument air supply; therefore, the demand is constantly changing. The other application of the HP compressors is PCI air supply. The PCI air, also known as transport air, is used to inject pulverised coal into the blast furnace.

Both demands supplied from the HP compressors are critical for production. Without PCI air the blast furnaces cannot operate efficiently. Without instrument air the final stages of production cannot be completed. Sufficient pressure of instrument air is also important to ensure good product quality. It can be concluded that proper HP compressor operation is critical. This results in certain constraints on the system.

Blast furnace demand

In Section 2.2 it was found that the compressed air supply to the blast furnace needs to be reliable and stable. The flow requirement of the blast furnace can only be changed if it is production-related.

The blast furnace also has a certain pressure requirement. The air supplied from the compressors is usually higher than this required pressure. The pressure reduction required for the blast furnace is achieved at the flow control station. At a specific flow, the blast furnace has a specific pressure requirement.

Since pressure and flow depend on each other, a drop in header pressure may result in less flow reaching the blast furnace. This depends on the valve response. To ensure sustainable operation, the flow to the blast furnace cannot be altered. The intervention chosen must ensure that there are no sudden changes in pressure or flow of the compressed air system.

Rate of change

When considering any intervention, the required rate of change is an important factor. For this type of system there cannot be any sudden large changes. It will result in the air supply becoming unstable, which may lead to the blast furnace becoming unstable. When the blast furnace becomes unstable, it may lead to production losses. An unstable supply of instrument air will also reduce product quality and result in increased repair costs.

The acceptable rate of change for a specific system needs to be determined by testing. Initially small changes can be made. The magnitude of the changes can be increased until signs of instability can be seen. For example; the pressure fluctuations and time to stabilise can be monitored to determine the stability of the system.

3.3 IDENTIFYING CRITICAL PARAMETERS

In order to determine what saving strategies to consider, the critical parameters first need to be determined. From this, the different strategies can be evaluated and the strategies that are not suitable be eliminated. The identified critical parameters on the system used for this study are given in the subsections that follow with a short discussion of each.

3.3.1 Critical parameters on the blast furnace

The critical parameters of blast furnace operation in terms of compressed air will be discussed first. The critical parameters identified on the demand side may result in additional critical parameters identified on the supply side.

Cold blast flow requirements

For proper blast furnace operation, a stable supply of compressed air is important. This is to ensure stable operation and a good quality product. Therefore, when selecting a saving strategy, it is important that it does not affect the compressed airflow of the system.

During normal operation the blast furnace sometimes changes the airflow requirement. This may be due to an operational problem, which requires a reduction in production tempo. When a flow set-point change is made, the new flow set point is expected to be reached

within a certain period of time. If possible, this period of time needs to remain unchanged after the intervention. A small deviation may be acceptable.

The best way to determine if the airflow requirement is met is to set up a graph comparing the set point and actual flow. This is shown in Figure 34 with the black line representing the set point and the red line the actual flow. The upward spikes are due to stove-filling after which the intermittent actual flow drops can be seen below the set point. It can also be confirmed that after a set-point change the actual flow reaches the set point within the required period of time. The downward spikes at approximately 20:00 are due to a large disturbance that occurred in the system. Occurrences such as these need to be kept to a minimum.

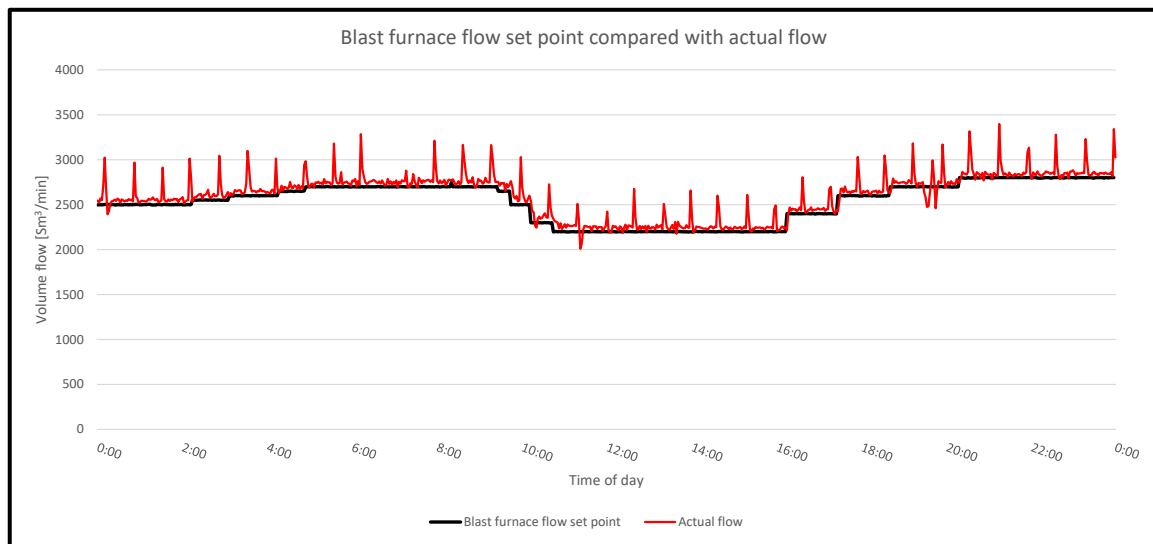


Figure 34: Blast furnace set point and actual flow

Stove-filling

Stove-filling rapidly increases the compressed airflow demand by 400 Sm³/min. It was found that the LP compressor header pressure would drop significantly due to this sudden increase in flow demand. Stove-filling control was implemented to compensate for this pressure drop.

Shortly before stove-filling starts, the compressors are ramped up, which increases the pressure in the LP compressor header. When stove-filling is in progress, the pressure in the header reduces back to the original pressure set point. Since it is a large system, stove-filling control results in header pressure fluctuations after stove-filling. An example of this is shown in Figure 35.

The black line on the graph shows stove-filling control. When the line drops to -1, stove-filling control is activated. The pressure in the header increases for approximately two

minutes after which the valve of the stove is opened. After the valve is opened, the header pressure drops significantly but does not go below the minimum of 340 kPa.

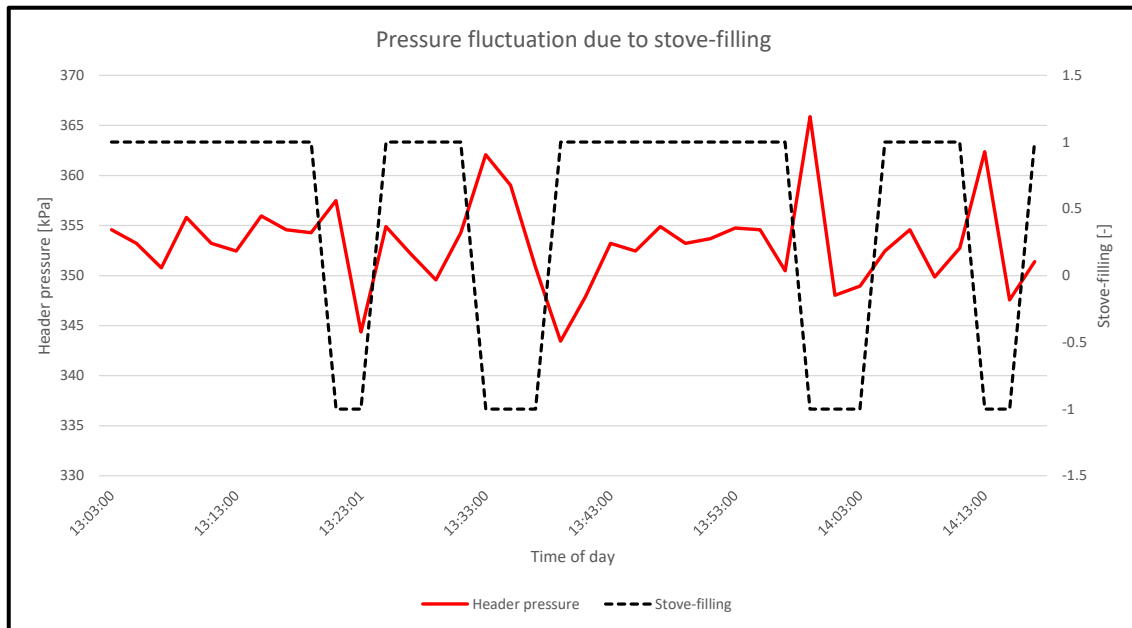


Figure 35: Stove-filling pressure fluctuation

Snort valve position

Under certain operational conditions it may be required to have a rapid decrease in airflow to the blast furnace. An example of this is when the blast furnace differential pressure becomes too high. The snort valve is opened to achieve the rapid decrease required. The snort valve is located before the blast furnace as shown in Figure 33. The result is a large flow of air through the snort valve and less air reaching the blast furnace. The snort valve is open for a short time, but it greatly influences the supply side.

Due to the increased airflow from the open snort valve, the LP compressor header pressure shows a significant drop. Before the snort valve is opened, the necessary precautions need to be taken. This will ensure that the LP compressor header pressure does not drop below the minimum allowable limit.

Figure 36 shows a worst-case situation of the snort valve opening. For the given situation it was required to release a large amount of air for a longer period than normal. This resulted in a significant drop in the header pressure as indicated by the red line.

From the black line it can be seen that the snort opened to approximately 40% for 16 minutes. Normally it opens to 25% for a few minutes; sometimes it opens for less than two minutes.

The opening of the snort valve had a large impact since no precaution was taken. The compressor plant was notified that the snort valve would be opened, but the large opening for the extended period was not expected.

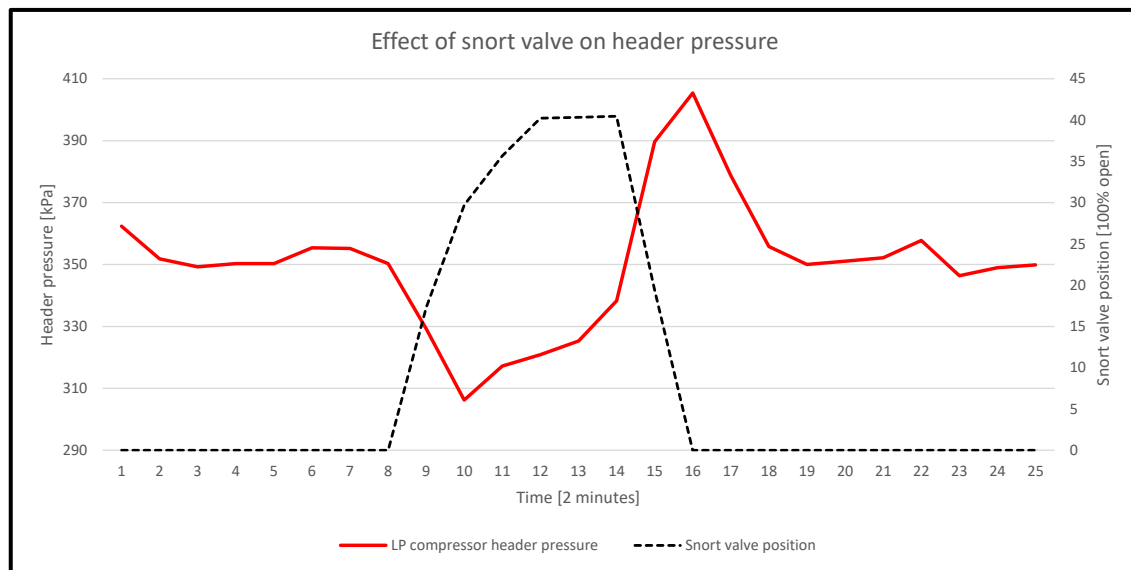


Figure 36: LP compressor header pressure fluctuation due to snort valve opening

Cold blast air pressure

The cold blast air pressure requirement is determined by several factors. The three most basic factors are the blast furnace top pressure, differential pressure and the pressure drop over the stoves. These factors add up to the cold blast air pressure requirement. This is a critical parameter that also needs to be considered on the supply side.

As mentioned in the previous point, it may sometimes happen that the blast furnace differential pressure becomes too high. This may result in the cold blast pressure becoming too low for the demand. However, it is also an indication that it may be required to open the snort valve. Therefore, the necessary precaution for the snort valve opening needs to be taken.

Flow control valves

High compressed airflow rates are required to operate a blast furnace. In order to achieve the high airflow rate, large pipes are used. This results in large valves being required to control the flow rate. The operating ranges of the valves used must be able to deliver the required amount of flow.

Since the flow needs to be stable, a two-valve configuration is used in most cases. A demonstration of this configuration is given in Figure 37. A primary valve controls the largest amount of flow and does not change often. A secondary valve, which is smaller than

the primary valve, is used to supply the remaining flow with the needed accuracy. The secondary valve is also used to supply the increased demand during stove-filling.

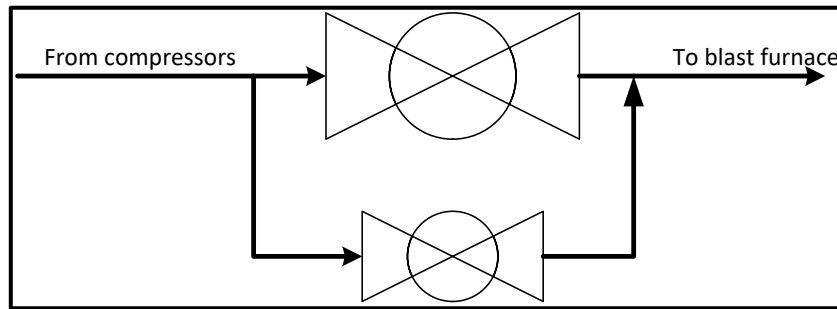


Figure 37: Two-valve configuration used for flow control

Due to the size of the primary valve it can only make small step changes with a fixed time delay between each. Numerous fluctuations will result in an unstable air supply and wearing out of the valve seat. The small valve is able to endure more fluctuation. It should, however, be limited to reduce wear on valve components.

3.3.2 Critical parameters on the compressor plant

The compressor system has several critical parameters due to the identified system constraints. From the critical parameters identified for the blast furnace, there are some parameters that also need to be monitored on the supply side.

LP compressor power and GVA

As discussed in Section 3.2, there are certain limitations on the LP compressors due to an upgrade. The maximum allowable GVA is limited to avoid overloading the compressor motor. For sustainable operation it is important to monitor the LP compressor GVA and power consumption. An alarm needs to be set up to guard against human error or negligence.

LP compressor header pressure fluctuations

The LP compressors supply compressed air to two blast furnaces of different sizes. Thus, the demand of each is different. The HP compressors are also supplied from the same header for further compression. Having three major consumers on the same header results in some pressure fluctuations.

As already discussed, stove-filling causes the largest fluctuation. The varying HP compressor demand also causes some minor fluctuation. When the HP compressor demand changes and stove-filling occurs simultaneously, it results in instability. The LP and HP compressor guide vanes counteract each other, resulting in LP and HP compressor header pressure fluctuations.

As an example, a situation where the HP compressor demand increases and stove-filling is triggered can be considered. Due to the increased LP compressor header pressure for stove-filling, the HP compressors operate unchanged at a higher demand. When the LP compressor header pressure decreases again, it moves past the set point due to higher demand from the HP compressors. In order to compensate for the lower inlet pressure, the HP compressor guide vanes open. Once the LP compressor set-point pressure is reached, the HP compressor discharge pressure is above its set point due to the HP compressor guide vanes opening. The result is the LP compressor guide vanes closing again due to an increased pressure in the header. The LP compressors once again miss the set point due to the HP compressors.

The above process repeats itself until the system reaches equilibrium again. Figure 38 and Figure 39 are simplified graphical representations of the system response. Figure 38 shows the header pressure and Figure 39 the GVAs of the LP and HP compressors. If possible, measures should be taken to shorten the time required to stabilise the system.

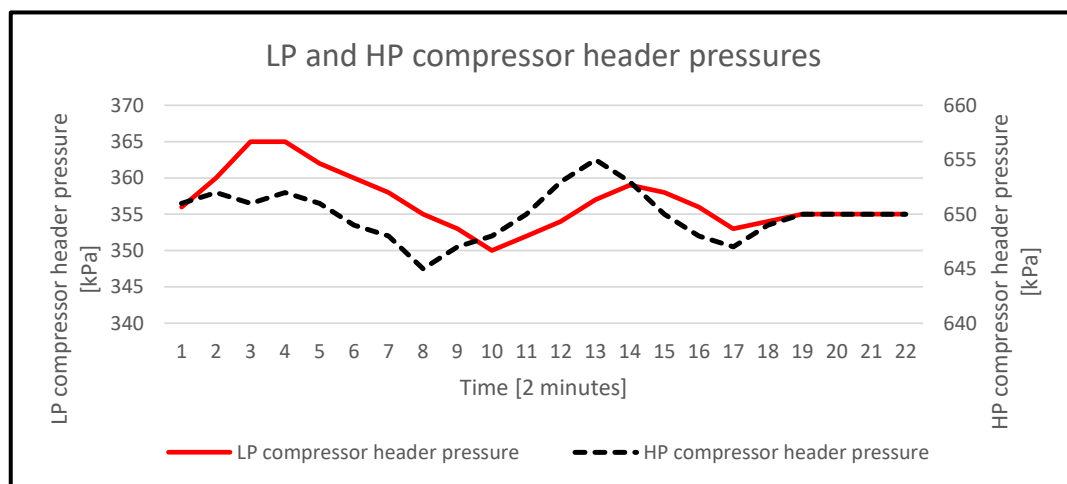


Figure 38: Pressure fluctuation during stove-filling and increased HP compressor demand

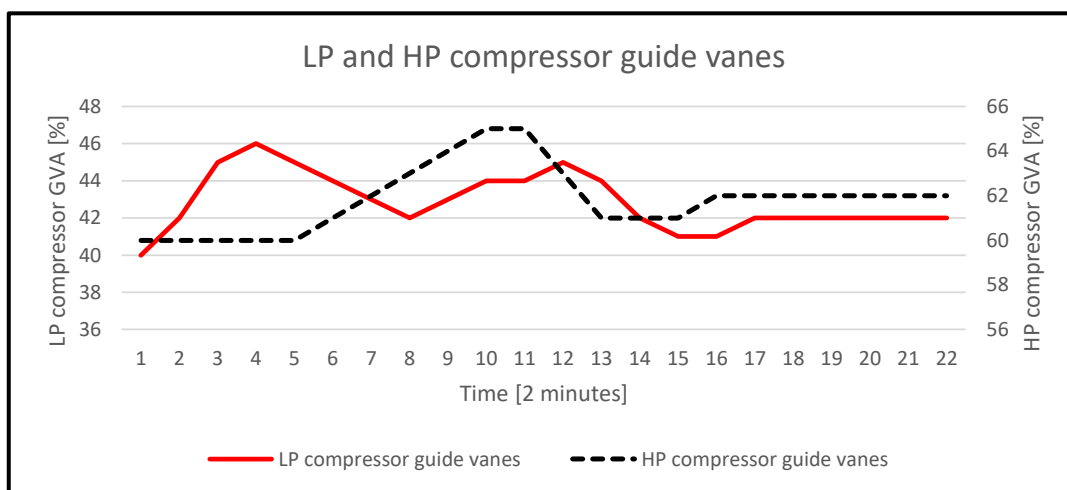


Figure 39: Simplified system response during stove-filling and increased HP compressor demand

Blow-off valve position

In certain cases, the demand on the LP compressors is low. There is usually an oversupply of air due to the limitations on the minimum GVA of the LP compressors. In order to get rid of this air, the blow-off valves of one or more compressors are opened.

Air lost through the blow-off valve is wastage and should be limited to a minimum. For the system under consideration it cannot easily be limited due to system constraints. It is, however, important to monitor and limit the wastage or use it for other processes if possible.

Instrument air pressure

Production plants usually have large instrument air networks. As in this case, a central supply provides the entire works with compressed air. Some points of demand are long distances from the supply, resulting in large pressure drops.

The supply of instrument air needs to be sufficiently high to accommodate even the furthest plants. An insufficient supply of instrument air pressure may result in product quality problems. In order to minimise the damage, the plant may stop and book a delay. Due to the possible costs involved, it is important to always monitor the instrument air supply.

3.4 DEVELOPING AN ENERGY SAVING STRATEGY

All the information gained previously will be used to develop an energy saving strategy in this section. This strategy will take the system constraints and critical parameters into consideration.

3.4.1 Centrifugal compressor theory

The specific system on which the strategy will be implemented has centrifugal compressors. The work done by such a compressor is given by Equation 6 [52]. This equation will be used to identify the parameters that can be varied to achieve an energy saving.

$$WD = \frac{k}{k-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] \quad \text{Equation 6}$$

With:

$WD = \text{Work done}$

$k = \text{Ratio of specific heat}$

$P_1 = \text{Inlet pressure}$

$P_2 = \text{Outlet pressure}$

$V_1 = \text{Volume flow}$

From Equation 6 it can be seen that only the outlet pressure and flow rate can be varied to achieve an energy saving on the compressors. The ratio of specific heat is a constant and cannot be varied for the given system. The inlet pressure of the compressor can also not be varied since it uses air from the atmosphere.

In order to decrease the work done by the compressor, the outlet pressure, flow rate or both need to be decreased. As discussed in previous sections, the blast furnaces require a specific volume of air for normal operation. Therefore, the reduction in flow cannot be achieved on the blast furnaces. Since the compressor supply pressure is higher than the pressure requirements of the consumers, this gives opportunity for energy saving. A reduction in flow on the instrument air can also be considered.

A factor that is not considered in Equation 6 is the compressor efficiency. The efficiency of the compressor changes for different points of operation. The efficiency is used in Equation 7 to determine the actual work done from the theoretical work calculated in Equation 6.

$$WD_{actual} = \frac{WD}{\eta_{compressor}} \quad \text{Equation 7}$$

The compressor motor also has an efficiency that will determine the electric power consumption. This efficiency also varies as the load on the motor varies. Equation 8 is used to calculate the electric power required by the compressor.

$$W_{electric} = \frac{WD_{actual}}{\eta_{electrical}} \quad \text{Equation 8}$$

An overall efficiency can also be used when Equation 7 and Equation 8 are combined. The resulting equation is given by Equation 9.

$$W_{electric} = \frac{WD}{\eta_{overall}} \quad \text{Equation 9}$$

$$\eta_{overall} = \eta_{compressor} \times \eta_{electrical}$$

In conclusion, for the specific system, the instrument airflow demand and LP compressor header pressure can be reduced. This will result in a saving achieved directly from the work done by the compressor. Another strategy is optimising the system in terms of efficiency. This can be achieved by operating certain compressors at a higher load than others. This strategy was illustrated in Figure 29 of Section 2.5.

3.4.2 Energy saving strategies

Several energy saving strategies for compressed air systems were identified in Section 2.5. In the sections thereafter, the system overview was discussed and operational constraints and critical parameters were identified. In this section the relevant strategies will be evaluated to identify a suitable strategy for implementation. Four of the possible strategies will be critically reviewed to determine which strategy can be implemented.

Reduce pressure set point

During initial investigation it was found that the pressure supplied by the compressors is higher than that required by the consumers. It was also found that the limiting factor is the HP compressors. The pressure supplied to the HP compressors needs to be sufficient in order to maintain the instrument air pressure.

The instrument air demand varies throughout the day. During normal operation, with a limited amount of misuse, the supply is sufficient. During other times, such as plant start-up and cleaning during shift change, the demand increases. This requires an increase in the LP compressor header pressure in order for the HP compressors to meet the demand.

One of the blast furnaces requires a minimum pressure of 340 kPa. However, this pressure is too low for the HP compressors. It results in the instrument air dropping below its minimum pressure during times of increased demand. Through testing it was found that a header pressure of 355 kPa is sufficient for normal operation. However, in times of increased instrument air demand, this pressure is no longer sufficient.

The conclusion of this strategy is that the header pressure set point cannot be reduced by a fixed amount. A minimum allowable pressure needs to be determined first. After this, the set point needs to be varied within the minimum and initial values as required by the HP compressors. The result will be a varying saving as conditions change. It is, however, the maximum saving that can be achieved for the given conditions of operation.

Limiting the number of compressors operating

The different points of demand on the system consume large amounts of air. A change in the amount of air required by the blast furnaces has a large impact on the compressors. There are certain constraints on LP compressor operation due to an upgrade as discussed in Section 3.2.2.

When the demand becomes low, the guide vanes of the LP compressor may decrease to below the minimum requirement. In order to compensate for this, the blow-off valves of some of the compressors are opened. The air going through the blow-off valves is wasted energy since it is not used for anything.

In ideal blast furnace operation, the air demand stays constant. Due to certain operational factors it is sometimes required to change the flow set point of the blast furnace. The changes are limited to a minimum to ensure furnace stability. In the case of a demand reduction, a time of lower demand is usually estimated. In these times, the option of unloading a compressor needs to be considered.

It needs to be determined what the minimum duration required to motivate unloading a compressor is. In the case of the duration exceeding the minimum, it needs to be determined if the demand can be supplied with fewer compressors. This can easily be done by subtracting the blow-off airflow from the total amount of airflow supplied. If this flow rate can be achieved after unloading a compressor, it would result in large energy savings.

In order to ensure that an energy saving is achieved, a feasibility calculation can be done. When a compressor is unloaded, it still consumes a certain amount of energy. It needs to be determined if the energy consumed is less than the energy wasted due to blow-off. If the duration of lower demand is long enough, the possibility of shutting down a compressor also needs to be considered.

In conclusion, it is important to closely monitor the blow-off flow and compressor operating point. A real-time calculation needs to be done in order to ensure that the minimum amount of energy is being consumed.

Split the air supply ring

Since the different points of demand require different pressures, splitting the supply ring should be considered. By doing this, the different consumers can be supplied according to individual needs. This could mean that only one compressor operates at a high pressure to supply the HP compressors. The pressure set point of the other compressors can then be decreased to the minimum for safe operation.

When the compressed air system was installed, it was designed with this strategy in mind. Therefore, the LP compressor header already has an intermediate valve installed. This valve, located between LP2 and LP3, as indicated on Figure 33, can be closed to split the header.

The blast furnaces were also upgraded on the demand side, resulting in an increased flow demand.

Although this is an effective saving strategy, it is not possible to achieve. The first reason is for emergency purposes. In the case of one LP compressor tripping, another is needed as soon as possible. The hydraulic actuated valve installed in the header reacts too slowly for an emergency situation.

The second reason is that due to the increased demand and piping layout, it is not possible to supply a combination of consumers. Table 2 displays the combination of flow demands during normal operation. It must be noted that the flow demands may be higher than in the table due to increased production targets.

Table 2: Flow demand ranges for blast furnace and HP compressor combination

Demand point	Individual demands	Total maximum demand	Available supply
Blast Furnace B	2 600	4 600	4 000 or 6 000
HP compressor	1 600		
Stove-filling	400		
Blast Furnace A	3 600	5 600	4 000 to 4 200
HP compressor	1 600		
Stove-filling	400		

From Table 2 it can be seen that when combining any one of the blast furnaces with the HP compressors, the demand cannot be met. In the case of Blast Furnace B, there will be an oversupply of air resulting in the blow-off valves opening. In the case of Blast Furnace A, the demand is higher than what can be supplied by the compressors.

From the constraints given in Table 2, the possible combination of demands was optimised in Table 3. For the given parameters, the Blast Furnace A side of the header will be able to supply the demand. On the Blast Furnace B and HP compressor side of the header, the demand cannot be met. It also needs to be considered that Blast Furnace B is able to operate at a lower pressure than Blast Furnace A. By combining Blast Furnace B with the HP compressors, which require a high pressure, the purpose of maximising the energy saving is defeated.

Table 3: Flow demand ranges after optimisation

Demand point	Individual demands	Total maximum demand	Available supply
Blast Furnace B	2 600	4 600	4 000 or 6 000
HP compressor	1 600		
Stove-filling	400		
Blast Furnace A	3 600	4 000	4 000 to 4 200
Stove-filling	400		

Match the supply with the demand

This strategy is a combination of the strategies discussed previously. No single strategy will maximise the amount of energy savings that can be achieved. By combining the different strategies, a maximised saving can be achieved at different times of day.

From the first strategy, the pressure set point can be varied according to the HP compressor demand. From the second strategy, the amount of air wastage is limited through real-time monitoring and calculations. The third strategy cannot be implemented without a shutdown and large capital expenditure.

If the capital required for splitting the supply ring becomes available in future, the savings achieved can be increased further. By splitting the supply ring and upgrading the piping layout, the supply can be matched according to each consumer. The HP compressors can be supplied by a single compressor and the blast furnaces by the remaining three compressors. The header set point on the blast furnace side can then also be adjusted according to the blast furnace demand.

In the following sections the simulation and simulation results will be discussed. The next step after the simulation is implementation on the actual system. In Section 3.5 the procedure for implementation and document requirements will be discussed.

3.4.3 Simulation of the compressed air system

A simulation was done using Process Toolbox. This software was specifically developed for industrial systems such as compressed air systems. The purpose of the simulation is to verify that the identified strategy does result in an energy saving.

Figure 40 shows the layout of the simulation. It can be seen that in the simulation only four compressors were used because one compressor is always on standby. Therefore, it will have no impact on the energy use of the compressed air system.

The four compressors feed into a common manifold. For the purpose of the simulation, each compressor has a controller to regulate the outlet pressure. This indirectly regulates the pressure in the common manifold.

After the common manifold the air is distributed to the different demand points with a piping network. The simulation was simplified to one pipe for each consumer. The pressure drop for each of the pipes is determined from actual data. The flow of each consumer is the average during normal operation. The assumptions that were made and simulation parameters used will be given and discussed next.

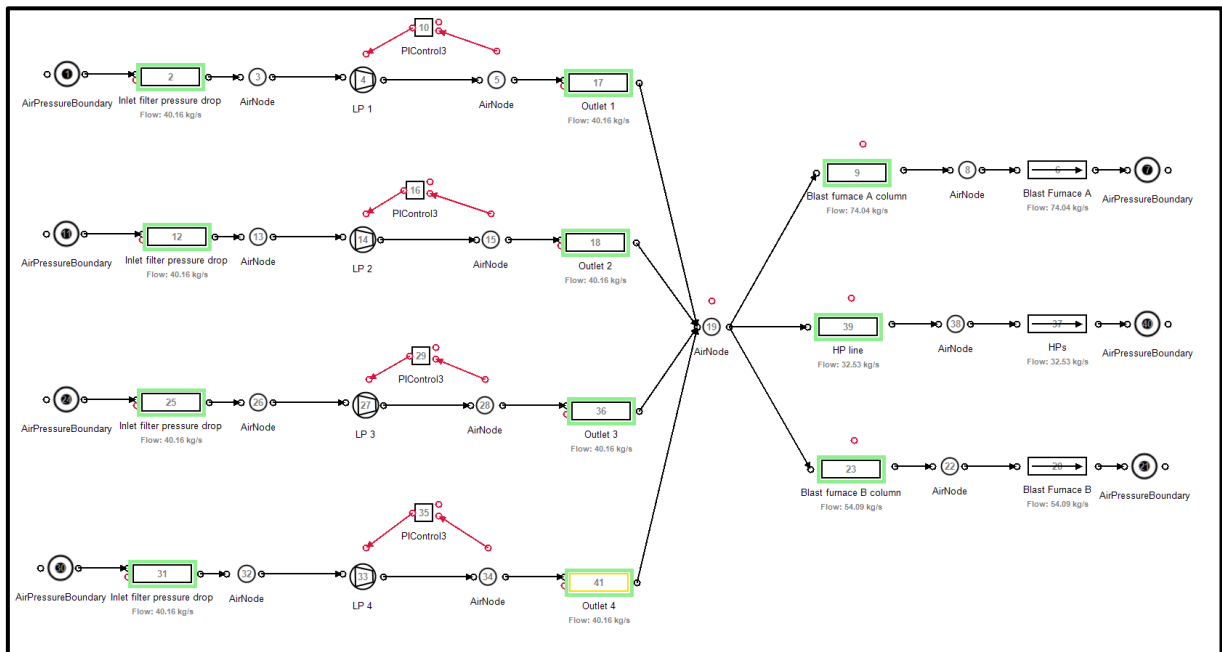


Figure 40: Simulation layout

Assumptions

Certain assumptions had to be made for the simulation, which are summarised as follows:

1. Points of demand require a constant stable flow of air.
 - In blast furnace operation, it is preferred to operate at a constant airflow rate. This is, however, sometimes difficult due to the complexity of blast furnace control. For the purposes of the simulation, the flow requirements of the two blast furnaces are assumed to be constant.

- The instrument air has a varying demand. The variation is dependent on many factors such as the number of plants operating and the time of day. The varying demand does not have any pattern or schedule. Therefore, in the simulation an average consumption figure is used as a constant demand.
2. The compressors are identical.
 - Four of the compressors are identical machines from the same manufacturer. The fifth compressor is identical to the others, but came from a different manufacturer. Therefore, actual performance of each is slightly different due to factors such as service time and manufacturer. Average performance values of all the compressors are used to characterise the compressors in the simulation.
 3. Initial header pressure set point was 375 kPa gauge.
 - During investigation, the LP compressor header pressure set point was found to be 375 kPa gauge. Therefore, the simulation will be used to simulate a baseline power profile at 375 kPa gauge as well as an optimised power profile.
 4. Ambient air pressure is 85 kPa absolute.
 - From the altitude of the system location it was determined that the ambient pressure was slightly above 85 kPa absolute. From actual historical data, the ambient pressure was found to be correct. For the purpose of simplification, the ambient pressure was taken as 85 kPa absolute.
 5. Ambient air temperature is 25 °C.
 - The temperature of ambient air varies throughout the day. It also varies according to the season. A conservative temperature of 25 °C was used for the simulation. This is the average maximum temperature at the location of the actual system.

After making the necessary assumptions for simulation purposes, the next step of the simulation could be taken. That is, determine all the required parameters to complete the simulation as accurately as possible.

Simulation parameters

The parameters used in the simulation are based on an actual system. The most important parameters are given in Table 4. The system consists of two blast furnaces and two HP compressors feeding from the LP compressor header. The LP compressor header is fed by

five LP compressors. During normal operation, only four compressors are in operation with one on standby.

Table 4: Simulation parameters

Parameter	Simulation value	Unit
Blast Furnace A flow demand	3 600	Sm ³ /min
Blast Furnace A pressure	321	kPa gauge
Blast Furnace B flow demand	2 600	Sm ³ /min
Blast Furnace B pressure	269	kPa gauge
HP compressor flow demand	1 600	Sm ³ /min
LP compressor power consumption	9	MW
LP compressor delivery flow	2 100	Sm ³ /min
LP compressor delivery pressure	375	kPa gauge
LP compressor efficiency	0.7	%
LP compressor motor efficiency	0.87	%
Polytropic coefficient	1.08	–

3.4.4 Simulation results and conclusion

After completing the simulation, the baseline power was found to be 34.8 MW. After lowering the header pressure set point of the simulation, the power consumption was found to be 33.6 MW. The power profiles resulting from the simulation are shown in Figure 41. The assumption of constant demand resulted in a constant power profile for the 24-hour period.

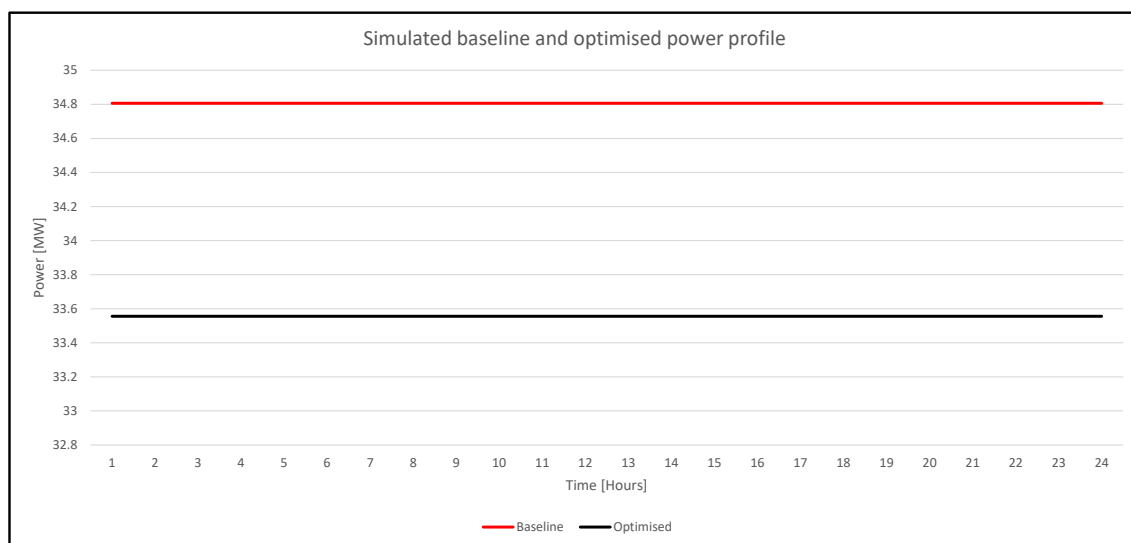


Figure 41: Simulated baseline and optimised power profile

In conclusion, it can be seen from the simulation results that the average energy saving that can be achieved is 1.2 MW. Testing and implementation on an actual system can now be done. In Section 3.5, the implementation of the energy saving strategy will be discussed in more detail.

3.5 IMPLEMENTING AN ENERGY SAVING STRATEGY

There are certain pre-implementation requirements for the system on which the strategy will be implemented. These include a control philosophy, risk assessment, HAZOP study and testing. In the following subsections, each will be discussed together with the required documentation.

Another important factor in implementation is proper communication. It needs to be determined whether the strategy can be safely implemented. The final step is approval from the system managers. Once this is completed, project maintenance can continue for as long as agreed.

3.5.1 Control philosophy

Before any strategy can be implemented, it must be clear what the intended deviation from the current control is. Therefore, the first step is to develop a control philosophy. The control philosophy contains all information on the proposed changes. It also identifies the critical parameters that need to be monitored.

In the control strategy, the only major deviation from the original control is lowering the header set-point pressure. The pressure is decreased by 20 kPa as in the simulation. When lowering the pressure in the header, it is important to consider the capabilities of the system valves and distribution pipes.

The major considerations in the control philosophy are the blast furnace flow requirements and the HP compressor demand. It is important to monitor the stability of the blast furnace flow to ensure sustainable operations. It is also important that the air required by the blast furnaces is available to them at all times.

On the HP compressor side it is important not to overload the compressors due to the lower inlet pressure. Once the HP compressors reach their maximum capacity at high demand, the instrument air pressure will start to drop. In such a case, the LP compressor header pressure needs to be increased to meet the demand.

The large flow control valves to the blast furnaces have a maximum opening restriction. This is done as a safety margin to limit the maximum amount of air that can be supplied by the valve. From testing it needs to be determined if the operating range is still sufficient at a lower pressure. If not, the maximum valve opening allowed needs to be adjusted as needed. This should only be done if it is safe to do so.

Since the maximum allowable valve opening was set to 75% in the past, it is assumed that the piping was not used to its full potential. During normal operation it was also not required for the valve to reach its maximum allowable opening. Due to this it was assumed that at the lower pressure the piping would still be sufficient to supply the flow requirements.

Through investigation it was found that in the past the system operated at 35 kPa lower than the current operation. Due to system expansion and upgrades the pressure was increased. The blast furnace flow requirements also increased during this time. It was, however, never determined what the minimum allowable header pressure was.

Due to the size and complexity of the compressed air system it was also necessary to define a minimum waiting period before making pressure set-point changes. The waiting period is determined by the time required for the system to stabilise after a large disturbance. Some disturbances that are considered to have a large impact are as follows:

- Stove-filling
- Header pressure set-point change
- Blast furnace flow set-point changes
- Large changes in instrument air consumption

In general, a rule of a minimum of 15 minutes waiting period was created. Additional to this, the other factors also needed to be considered. When the blast furnaces increase their flow set points or stove-filling is taking place, the pressure set point cannot be decreased. This increases the final pressure drop in the header after these processes.

When the HP compressors are not fully loaded, but the instrument air pressure is below its target, the set point cannot be decreased either. This will result in a further drop in instrument air pressure. During and after testing some minor changes had to be made to the control philosophy.

As discussed in the introduction of this chapter, developing a control philosophy is an iterative process. In the following subsections the remaining steps of the iterative process will be discussed.

3.5.2 Risk assessment

The possible risks can be determined from the control strategy. A risk assessment is the first step in ensuring that the strategy is safe to implement. The different components of the compressed air system and their operation were considered. From this, the possible risks were identified and prioritised.

The largest risk for this intervention is production loss. Production loss at the blast furnace can be caused by problems with the compressed air system. The compressed air system does not always directly cause production loss. It can, however, cause furnace instability. Due to furnace instability, the production rate needs to decrease.

Slag in the air pipes is a risk that would cause production loss and high repair costs. This is the result of the compressed air supply to the furnace suddenly falling away due to a power failure or a faulty valve. The solid raw materials inside the furnace drop to the hearth, causing the liquid material to push up to the tuyères. The slag floating on top of the liquid iron enters through the tuyères, burns the PCI lances, and flows into the bustle pipe. Once the slag solidifies, the pipe section needs to be removed in order to remove the slag.

A summary of the factors that could cause production loss is as follows:

- Insufficient flow of compressed air supplied to the blast furnaces
- Incorrect pressure supplied to the blast furnaces
- Defective valves
- Incorrect measurements from field instruments
- Power failure on compressor supply

Another risk that is important to consider is overloading the HP compressors. As discussed in earlier sections, the HP compressors supply instrument air to all secondary production processes. When the pressure is insufficient, some of the processes need to stop for quality reasons. This needs to be avoided due to the costs involved.

The next step in the process is a HAZOP study. In this study, a wide variety of factors that may be hazards are considered.

3.5.3 HAZOP study

The aim of the HAZOP study is to determine all the possible hazards due to project implementation. It also determines the possible causes of each hazard and the corrective action required.

After completing the HAZOP study, a formal HAZOP meeting is needed. There are strict requirements for a HAZOP meeting; it needs to be determined if all the known hazards have been identified. It also needs to be decided if corrective actions are satisfactory.

In most cases, the corrective action is to increase the set point to a more stable point or return to original operating conditions. In a case such as power failure, the standard operational procedure before implementation needs to be followed. The control philosophy iterative process needs to be followed until the HAZOP is approved. Once it is approved, system testing can start. The HAZOP document is not included in the study due to confidentiality.

3.5.4 Testing of the strategy developed

With the control philosophy, risk assessment and HAZOP study approved, the necessary preparations for testing can be done. In this section the test procedure, emergency procedure and criteria of success will be discussed.

Test procedure

The aim of testing is to determine if the header pressure can be safely lowered by 20 kPa. The test procedure is developed in such a way as to minimise system instability. The test procedure is based on slowly reducing the pressure. The pressure is lowered by 2 kPa after which time is given for the system to stabilise. After the system has stabilised, the pressure is once again lowered by 2 kPa. The final step is a reduction of 1 kPa. The total 5 kPa reduction is the reduction target per day.

The system is kept at the reduced pressure for 24 hours. During this time the system is closely monitored. Included in the test procedure are the critical parameters that need to be monitored. If there are no problems during the 24-hour period, the next 5 kPa reduction can be done in the same steps as previously. This process is repeated until the 20 kPa reduction is achieved.

Emergency procedure

The emergency procedure is included in the testing procedure document. The procedure is limited to the factors that can be influenced due to testing. An example of this is the LP

compressor header pressure dropping below the minimum value. There are many factors that can cause this to happen. The exact cause needs to be determined as soon as possible after corrective action has been taken.

In most cases, any emergency would require the set point to be increased again. The severity of the emergency will determine the value by which the set point needs to be increased. When it is safe to do so, the emergency needs to be reported to the relevant persons such as the compressor plant manager and project manager. Therefore, the necessary contact details are included in the emergency procedure.

For emergencies due to factors not influenced by the project implementation, the normal operating procedure needs to be followed. An example of this is a power failure. For a situation such as this, there is already a procedure in place that needs to be followed. Operators of the compressor plant receive the necessary procedural training before starting work.

Criteria of success

Specific success criteria need to be developed in order to determine whether the test was a success or not. As mentioned earlier, the aim of the test is to determine if the set-point pressure can be safely lowered by 20 kPa. This can be translated to criteria of success with the following points:

- LP compressors operate within allowable ranges
- Pressure in the LP compressor header is stable
- Flow supply to blast furnaces is undisturbed
- System valves are able to supply the required flow
- HP compressors are not overloaded
- Instrument air pressure is sufficient

If the above criteria are satisfied, the test is considered to be success in which case the project can be implemented fully. This will be discussed further in the following sections. If the criteria have not been met, another iteration of the control philosophy needs to be done.

3.5.5 The importance of proper communication

In order to ensure safe operation, it is important to have proper communication. During the testing phase it is important to give the plant manager feedback on a daily basis. The end point consumers also need to be consulted for any operational problems.

During the first phase of testing, a responsible person such as the project engineer needs to be present in the control room. This is to closely monitor the system and assist in decision-making. Also, in the case of an emergency it is easier to report the situation if there is an extra person available.

A daily meeting with the blast furnace personnel needs to be arranged during testing. This is to ensure that there are no concerns or operational problems. Due to the number of instrument air-consuming plants and availability of personnel, it is not possible to have a meeting with each plant. In the case of a problem, the specific plant can notify the compressor personnel. The instrument air pressure needs to be monitored to minimise the risk of problems.

Proper data analysis needs to be done after each 24-hour test. This can be done using a template with graphs and tables showing the critical parameters. The interpreted results can be summarised in an email and sent to the relevant personnel.

Once the reduced set-point operation has been found to be safe, the system can be monitored from a remote location. At this stage it is important to communicate any changes per email to ensure traceability.

3.5.6 Approval process

As mentioned in the previous section, it is important to have a trace of all communication. This will assist in the approval process. In order to get approval to proceed, a meeting should be arranged to present all the results and discuss concerns, if any. It is important to have someone from the following departments at the first meeting:

- Compressor plant management
- Compressor plant maintenance
- Compressor plant instrumentation
- Blast furnace management
- Blast furnace instrumentation

The results of the system response due to the intervention should be presented. Any concerns identified from the results need to be reported. After the first meeting, the concerns identified need to be investigated and addressed.

Another meeting can be arranged with those involved with the identified concerns. If all parties are satisfied that it is safe to continue, the final steps of implementation can be

completed. These steps include operator training, implementation of the control system and real-time monitoring.

3.6 SUMMARY

This chapter presented a method for implementing compressed air energy saving strategies on an iron production plant. In order to illustrate the development of the method, it was applied to an actual system. By using the methodology, an energy saving strategy was identified and implemented on an actual system.

In the simulation section it was determined that a 20 kPa pressure reduction would result in a demand reduction of 1 250 kW. In the next section the results of the implementation will be given. In Chapter 4, verification and validation of the energy saving will be done. There it will be determined if the strategy was successful in achieving energy savings on an actual system.

4 RESULTS

4.1 PREAMBLE

In a previous section the different compressed air energy saving strategies were identified. The strategies that are relevant to the system considered in this study were evaluated. The best-suited strategy was selected and implemented.

In this section the results of the implementation of the strategy will be discussed. This will be done with verification and validation through case study. In the final part of this section a short summary of the results will be given.

4.2 VERIFICATION CRITERIA

For the purposes of verification, it is necessary to set up verification criteria. With these criteria it will be determined if the saving strategy is suitable for the given system. The system constraints and critical parameters are used to determine the criteria that need to be satisfied. The most important factor is to determine if the predicted saving amount is realistic. This is done by comparing the simulation result to the theoretical result.

Table 5 shows a list of the items identified in the verification criteria. Also given in this table is the importance of each item. The importance is ranked according to criticality for normal operation. A value of 1 is most important with a value of 3 being least important.

Table 5: Verification criteria

Criteria	Importance
Theoretical comparison	1
Compressors are able to supply required flow	1
Instrument air supply pressure is sufficient	1
HP compressors are not overloaded	2
Header pressure fluctuations are within limits	2
System valves does not fluctuate excessively	3

The items that are considered to be most important will be discussed first. The most important item is the theoretical calculation comparison. This is the first step in verification to ensure that the identified saving value is realistic. In the case that the answers of the two methods differ greatly, the cause needs to be determined. Once the difference is within a suitable limit, the process can proceed.

The most important item on the system side is the ability of the compressors to supply the required amount of volume flow. The LP compressors are a critical component on the system under consideration. They need to be able to supply the required volume at all times. This needs to be done without exceeding the operational constraints. The operational constraints were put in place to ensure sustainable operation.

The overloading of the HP compressors is an item that is dependent on the LP compressor operation. By decreasing the LP compressor header pressure, it could result in the HP compressors operating at maximum load. Operating the HP compressors at maximum load for long periods could result in compressor failure. The HP compressors are critical for instrument air supply. The instrument air supply will be discussed next.

As discussed in previous sections, the instrument air is used throughout the works. It is used for general applications such as actuators as well as other critical components. These critical components require a stable supply of compressed air to ensure product quality; for example, shape roll and air-levitated bearings. An insufficient supply of compressed air leads to production losses. Figure 42 shows an example of a defect due to insufficient air supply. The defect shown is known as alligatoring. There are many factors contributing to the occurrence thereof, of which rolling parameters are one. The rolling parameters are changed with the variation in air supply.



Figure 42: Shape roll defect: alligatoring

The LP compressor header pressure fluctuations are considered to be less important. The reason for this is that the pressure fluctuations would not have an immediate effect on the system operation. It is also not a continued impact, since the pressure fluctuations are mostly the result of a certain disturbance in the system. A fluctuation in header pressure will cause the system to respond accordingly. For example, the flow control valves to the blast furnaces will open or close as required. However, the fluctuations in the header pressure during no disturbances need to be minimal.

In the previous paragraph, it became clear that some of the system valves need to fluctuate due to disturbances in the system. Fluctuations cause wear on the valve seats and should therefore be monitored. After a disturbance, the valve needs to stabilise within the shortest time possible. This would reduce wear on the valve and result in less header pressure fluctuation. Figure 43 shows an exploded view of a ball valve with the yellow parts on both sides of the ball being the seats.

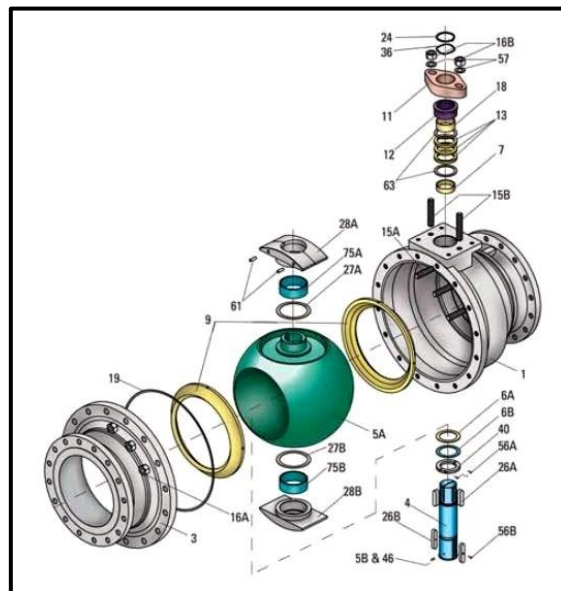


Figure 43: Exploded view of ball valve [53]

Valve fluctuation is considered to be the least important since it does not cause any immediate effects on system operation. In the long term, however, it could cause valve failure and large financial expenditure.

In conclusion, there are various items that need to be considered in the verification criteria. The importance of each varies according to the impact on the system. In the next section these criteria will be used to determine if the strategy implemented is sustainable.

4.3 VERIFICATION OF ACHIEVABLE ENERGY SAVING

The most important aim of verification is determining if the savings can be achieved sustainably with the identified strategy. In this section the verification criteria identified in Section 4.2 will be used to determine if the savings can be achieved sustainably. Each criterion is considered individually with the results of each given.

Theoretical calculation

Equation 6 from Section 3.4.1 is used for this part of verification. It was determined what the reduction in work done would be for a reduction of 20 kPa in the header pressure set

point. The flow is kept constant in the calculation because of the given strategy; only the pressure would be changed.

The result of the work done is shown in Table 6. As discussed in Section 3.4.1, the electric power consumption can be calculated from the work done. The centrifugal compressors used in the study are known to have a high efficiency. Therefore, for the purpose of this calculation and based on actual system performance, an overall efficiency of 0.8 was used. The resulting electric power is also shown in Table 6.

Table 6: Compressor work done and electric power consumption

	Before intervention [kW]	After intervention [kW]	Saving amount [kW]
Compressor work done	29 204	28 241	963
Electric power consumption	36 505	35 301	1 204

The theoretical value shown in Table 6 is compared with the simulation value in Table 7. In the last column the difference between the two methods was found to be 3.7%. The difference between the two methods is relatively small.

Table 7: Simulation compared with theoretical electric power saving

	Simulation [kW]	Theoretical [kW]	Percentage difference [%]
Electric power saving	1 250	1 204	3.7

The reasons for the 3.7% difference between the two methods also need to be considered. The first reason is due to the efficiencies being considered. The simulation uses a polytropic coefficient and two efficiencies (compressor and motor) to calculate the electric power. Compared with the overall efficiency of the theoretical calculation, it should result in a small difference.

Figure 44 shows a scatter plot of the theoretical and simulation power at different set points. The trend lines, being almost parallel, show that the changes in power for the two methods are similar. From the linear correlation R-squared value it can be seen that the theoretical method is perfectly linear. The simulation, however, is almost perfectly linear. This is since

the simulation is sensitive to changes in flow. The different points of demand do not have the exact flow as they should have. They are only accurate within the first tenth of a decimal.

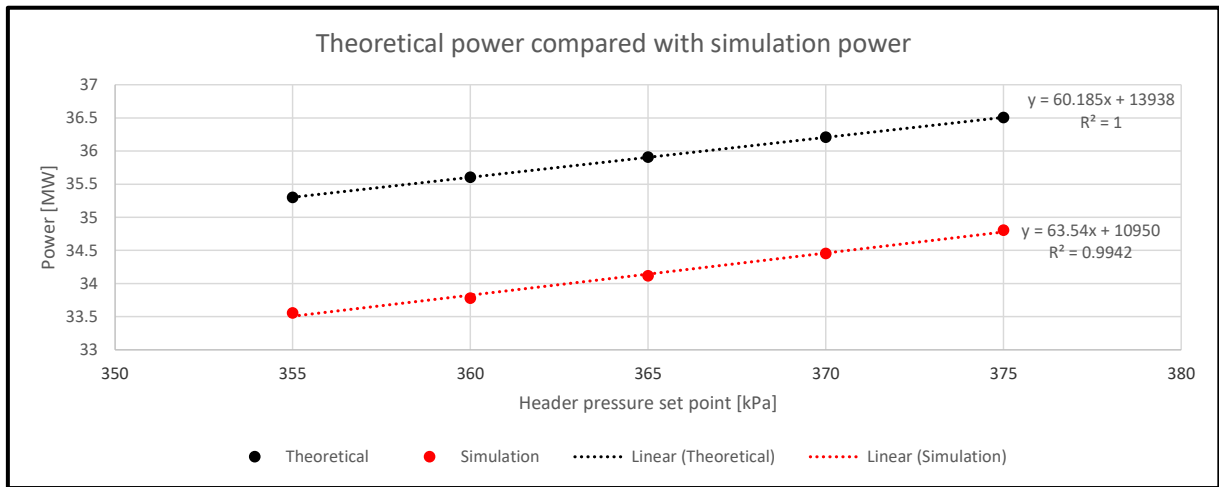


Figure 44: Theoretical power compared with simulation power

Due to the reasons given above, there will be a difference between the simulation and theoretical values. Due to the percentage difference of 3.7% being very low, the results can be accepted as true.

Required flow supplied by LP compressors

From the system constraints it is known that there is a maximum GVA limitation on the LP compressors. This constraint is put in place to limit the compressor electric motor power consumption to 9.6 MW.

The simulation was used to determine if the compressor would be able to supply the required flow before reaching the maximum power limit. For comparison purposes, the theoretical calculation was also used to ensure that the flow requirements could be met by the compressors. It was found that for both methods the flow requirements of the system can be met at the lower LP compressor header pressure.

HP compressors are not overloaded

Figure 45 shows a generic compressor performance map used for illustrative purposes. On the x-axis is the volumetric flow; on the y-axis, the pressure ratio as $P_{delivery}/P_{supply}$ (indicated as Pd/Ps). For this specific example in the figure it was determined if the compressor would be able to supply a certain range of flow at a given pressure. For this study it needs to be determined if the compressor would be able to operate at a higher pressure ratio without surging or choking.

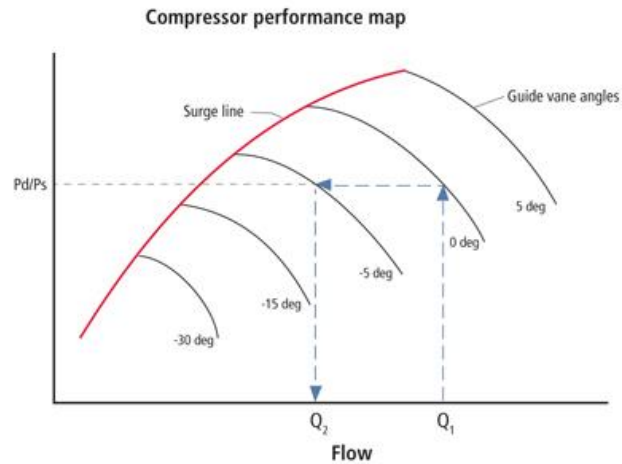


Figure 45: Generic compressor performance map

In order to determine if the lower inlet pressure of the HP compressors would not harm the machines, the specific HP compressor's performance maps were considered. It was found that for average operation, the higher pressure ratio required is within operational limits of the HP compressors.

During times of high demand, the required flow becomes too high for the new pressure ratio, which may cause choking. It can be seen in Figure 45 that a decrease in pressure ratio will result in a higher flow. Therefore, as discussed in Chapter 3, the LP compressor header pressure needs to be increased for these periods. This is not a regular occurrence and, therefore, the average power saving would still be achieved.

Instrument air pressure is sufficient

In the previous point it was determined that the HP compressors would not be overloaded under normal operation. Due to this, the instrument air pressure would also be sufficient. In times of high demand, the instrument air pressure may show a small reduction before corrective action is taken.

Header pressure fluctuations are within limits

As already discussed, there will be some pressure fluctuations due to system disturbances. Stove-filling is the disturbance that occurs the most. Opening the snort valve is the disturbance with the largest impact. If there is no disturbance, the header pressure should be stable.

The pressure stability during periods of no disturbance is determined by compressor operation. The compressor should be able to maintain the pressure at a set point with a

variation of one or two kilopascal. For the given system, this is considered to be stable operation.

A test had to be done on the system for verification purposes. During testing it was found that at certain set-point pressures the compressors were unable to stabilise. The fluctuation at the specific set point was larger than that at other more stable set points. These unstable set points are, therefore, avoided. The pressure set point is changed in such a way to exclude the unstable points.

During normal operation the header pressure was found to be stable. The effect of stove-filling varies according to the demand. At high demand it does not have a large impact, but at low demand the impact increases. The fluctuation is, however, within reasonable limits.

Opening of the snort valve sometimes result in the header pressure dropping below the minimum level. It is not often required to open the snort valve and it is not considered to be normal everyday operation. The compressor plant is informed before the snort valve is opened. In this case, the header pressure can be increased before the snort valve is opened.

Limited system valve fluctuations

During normal operation, the fluctuation of the flow control valves is within limits. Due to the pressure increase for stove-filling on one furnace, the flow control valve of the other needs to close slightly. After stove-filling, the pressure drop in the header requires that the valve opens again. Until the header pressure stabilises, the valve will fluctuate slightly. The valve usually stabilises within five minutes.

It was also found that due to system configuration, the small control valves sometimes fluctuate between fully open and fully closed. This occurs at certain ideal conditions and is shown in Figure 46. The compressor pressure set point and blast furnace flow set point need to be at the correct point for this to happen.

This is not a regular occurrence and, therefore, the solution is to change the pressure set point. By changing the set point, the valve will stabilise. After stabilising, the set point can be slowly returned to its original point.

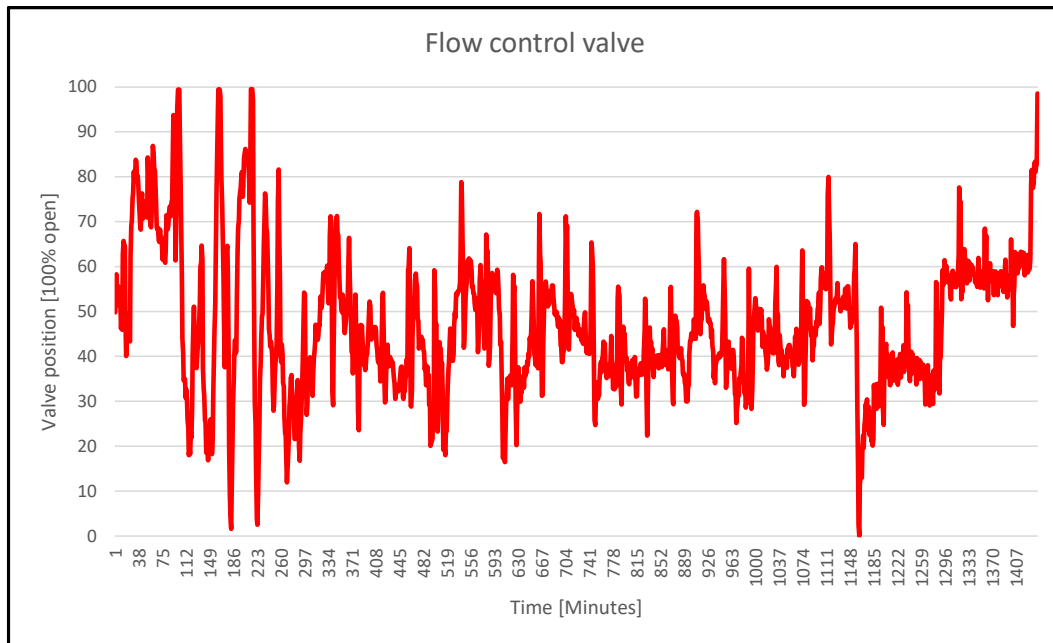


Figure 46: Small flow control valve excessive fluctuation

4.4 VALIDATION THROUGH CASE STUDY

For the purposes of validation, a case study was considered. The system that was used in Section 3 will also be used for the case study. In the case study it is determined if the energy saving strategy can be successfully implemented to achieve an energy saving. The first step was to fully implement the strategy and test for sustainability. Once the strategy was found to be sustainable and safe, a saving validation test could be done.

As discussed in a previous section, during the first set of testing all the major concerns were addressed. These included ensuring that the required amount of air reached the blast furnaces and did not overload the HP compressors. After this, the pressure set point could be held at the minimum for the specific circumstances.

After the first set of testing was completed and with approval to proceed, the strategy was fully implemented. The system was monitored for a month to ensure that all the minor concerns could be addressed. The parameters that had to be monitored are given in Section 3.3 – Identifying critical parameters.

During the month after implementation, some minor concerns had to be addressed. Due to the extended period it did happen that the HP compressors reached their maximum capacity. This required an increase in the LP compressor header set-point pressure. The result of this was a decrease in the energy saving that could be achieved for that specific period of time.

Despite the minor concerns, the strategy was found to be sustainable in the long term. It was, however, required to set up an alarm system to notify the operators of a set-point change. The set-point changes are done manually due to the unpredictability of the system. Although the set-point proposal is done automatically, it requires human judgement to make the final decision. Any predicted sudden changes in the system are communicated telephonically. This communication cannot be taken into consideration in the automatic control.

The final step was saving validation. The implemented strategy required a change in the compressor supply pressure. Therefore, when validating the saving, the pressure had to be the only varying parameter. For the given system this was difficult to achieve since the demand varied constantly.

The first step in validating the saving was to consider the LP compressor performance maps. Since the compressors were assumed to be identical, only one compressor was tested and mapped. This map was used to calculate the saving that could be achieved on all the compressors. The second step in validating the saving was an actual test on the compressors. This is referred to as a drop test since the saving achieved is calculated after dropping the pressure. Each of these steps will be discussed in more detail next.

4.4.1 Compressor map saving validation

Figure 45 is a generic representation of a compressor map in terms of the pressure and flow. On an actual performance map, the power is also shown on a separate graph that aligns with the flow. An example of such a map is given in Figure 47. Due to confidentiality, this is not the performance map of the case study system. It is only used for illustrative purposes, with the results being for the actual system.

For the compressor map under consideration a fixed inlet pressure was specified. Therefore, the outlet pressure is given on the y-axis. Since the inlet pressure is known, this can easily be converted to a pressure ratio if required.

Since the compressor performance map is very dense, a method to reduce the chance of mistakes was developed. The compressor map was simplified to a power profile at each of the two different pressure set points. A horizontal line is constructed at the initial pressure on the map. At each GVA shown on the map, the corresponding flow and power values were taken by constructing a vertical line at the point of intersection. The same was done for the lower pressure set point.

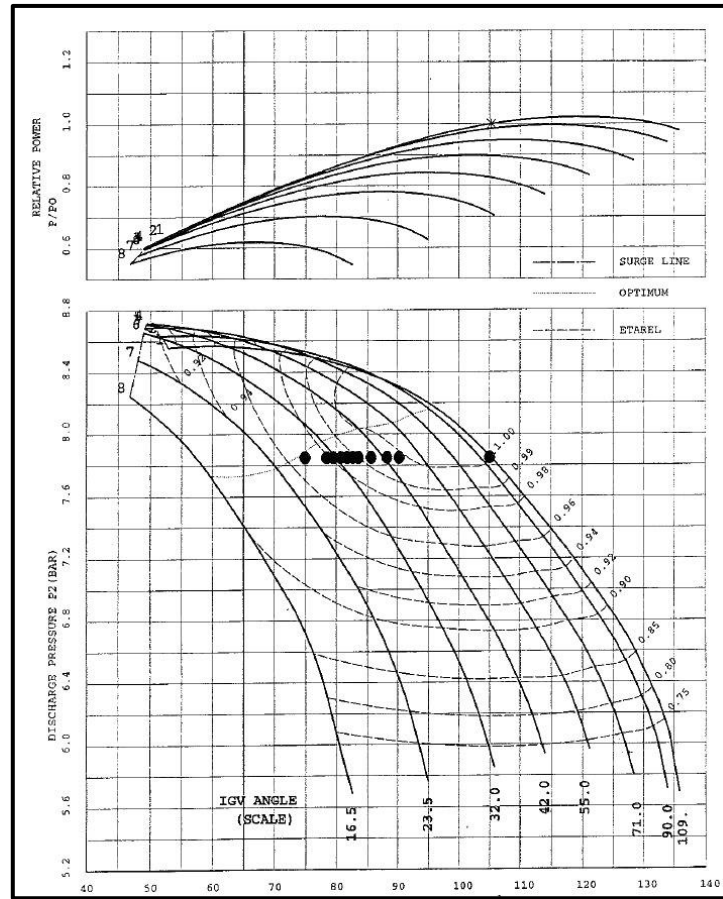


Figure 47: Typical actual compressor performance map

The result is six matching flow and power data points for each of the pressure set points. These data points were plotted and a second-order polynomial regression was done. The resulting profile and regression models are shown in Figure 48.

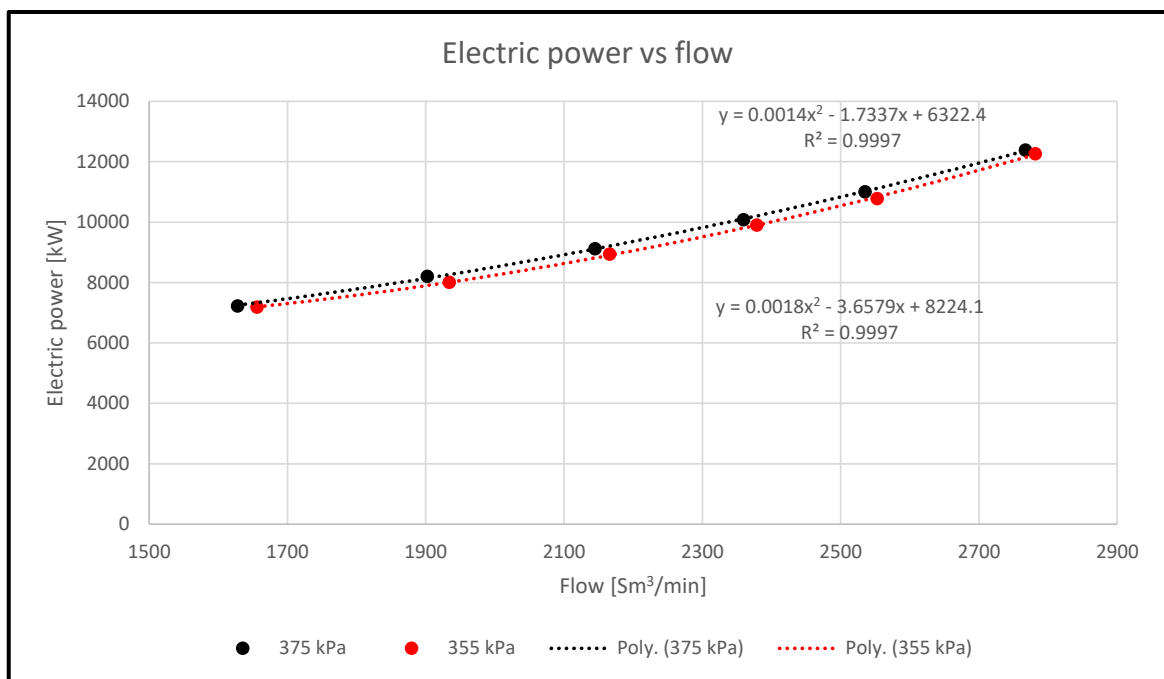


Figure 48: Compressor performance map power profile result

The regression models are used to calculate the power consumption at the different set points. As discussed earlier, the flow before and after implementation need to stay constant. Therefore, the same flow is used for each of the models to determine the power consumption before and after implementation. The flow used ($7\,858\text{ Sm}^3/\text{min}$) is the same for both the simulation and theoretical calculation. The result of the calculation is summarised in Table 8.

Table 8: Compressor performance map saving validation results

	Total power [kW]
Before implementation	33 278
After implementation	31 939
Saving due to 20 kPa reduction	1 339

It can be seen from the results that the compressor performance map validated saving is within 6.6% of the simulated value. A major reason for the difference may be due to difficulty in reading the compressor map. With a difference of only 6.6% the results can be considered to be true.

4.4.2 Drop test saving validation

The system was monitored closely and production schedules were considered. From this, a suitable time for doing a drop test was determined. A time when the flow demand was relatively constant was used. If the blast furnaces were to have a flow set-point change, the test had to be restarted. The result is an unknown, limited time period being available for doing the test.

For the purposes of the test, the pressure set point was changed in 5 kPa intervals. For operational reasons, the test was started at the minimum pressure after which it was increased in 5 kPa intervals. The system was given time to stabilise at each set point.

The time at which the system stabilised was taken as the starting time. When a major disturbance such as stove-filling occurred in the system, the test was stopped. For the time period of stable operation, the average power consumption and average flow were calculated. This process was repeated for each 5 kPa interval.

The energy saving of each interval was added together to determine the total saving due to the 20 kPa pressure reduction. The results of the saving validation test are given in Table 9.

The results are given in terms of a reduction from the maximum pressure. The saving for each interval is given as well as the cumulative saving at that interval.

Table 9: Drop test validation results

Header pressure set point [kPa]	Electricity saving [kW]	Cumulative saving [kW]
375	0	0
370	290	290
365	154	444
360	336	780
355	281	1 061

From Table 9 it can be seen that the saving validated with the drop test is lower than the expected saving. There are two major reasons for this: the airflow demand during the test; and the irregular saving value at 365 kPa. The drop test was started at an average airflow rate of 7 683 Sm³/min. This flow rate was lower than that used previously for the other methods of verification and validation.

The variation in flow rate may be the cause of the irregular result at 365 kPa. Figure 49 shows the cumulative savings profile for the different amounts of pressure reduction. At a reduction of 10 kPa, equivalent to a 365 kPa LP compressor header pressure, the linearity of the cumulative saving was disturbed. Although the differences in flow rate at the different points were compensated for, the effect at this specific point might have been too large for proper compensation.

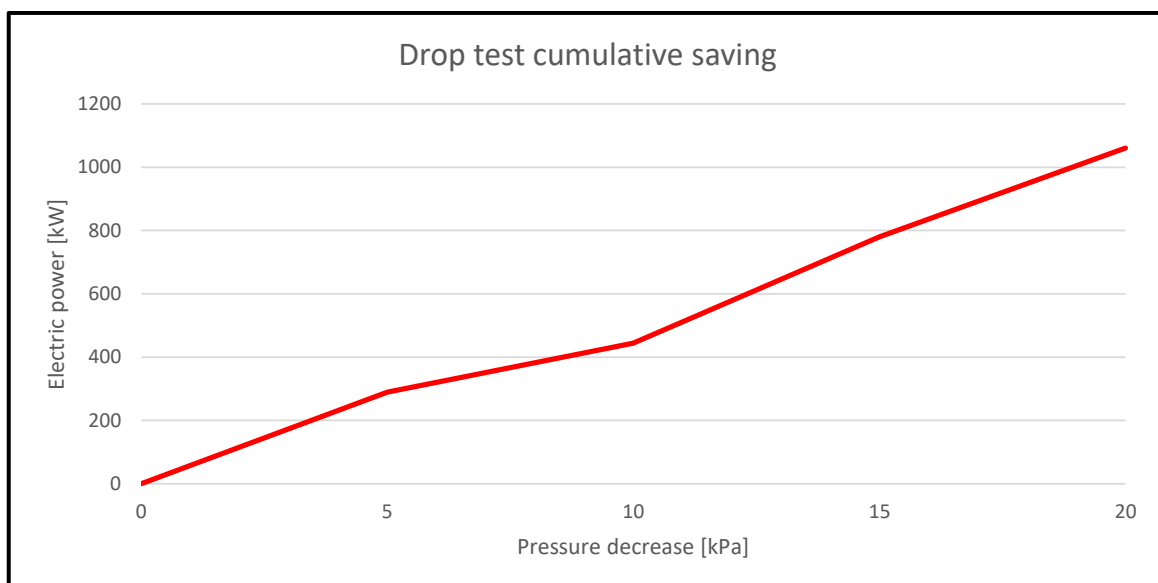


Figure 49: Drop test cumulative saving

A major problem with the drop test is the system stability in general as well as the stability of the flow. During the test the flow did change, resulting in a less accurate determination of the actual saving. This was compensated for with a general rule based on an assumption. For the given system it was determined that for each 1 Sm³/min change in flow, each compressor had a 1 kW change in power. This was determined from continuous monitoring for long periods and from mathematical calculations.

The conclusion was that the drop test could not be accepted as the final method of validation. Additional to the drop test, an alternative method of validation was considered. This method did not require the system to be stable in terms of flow. The basic idea of this method was the mathematical modelling of the system at the different pressure set points. The model was in the form of a linear regression.

Data over a long period of time was used for this validation method. A total of 922 data samples at each header pressure set point was used. By using a wide range of data, the system fluctuations became negligible. The linear regression at the initial 375 kPa and final 355 kPa set points delivered a good R-squared value. The linear regressions and R-squared values at each set point are given in Table 10. The scatter plot and regression line for the 375 kPa and 355 kPa set points are given by Figure 50 and Figure 51 respectively.

Table 10: Linear regression models at different set points

Set point	Linear regression	R-squared
375 kPa	$y = 5.0294 x - 4\,377.7$	$R^2 = 0.8993$
355 kPa	$y = 3.6092 x + 5378.1$	$R^2 = 0.9807$

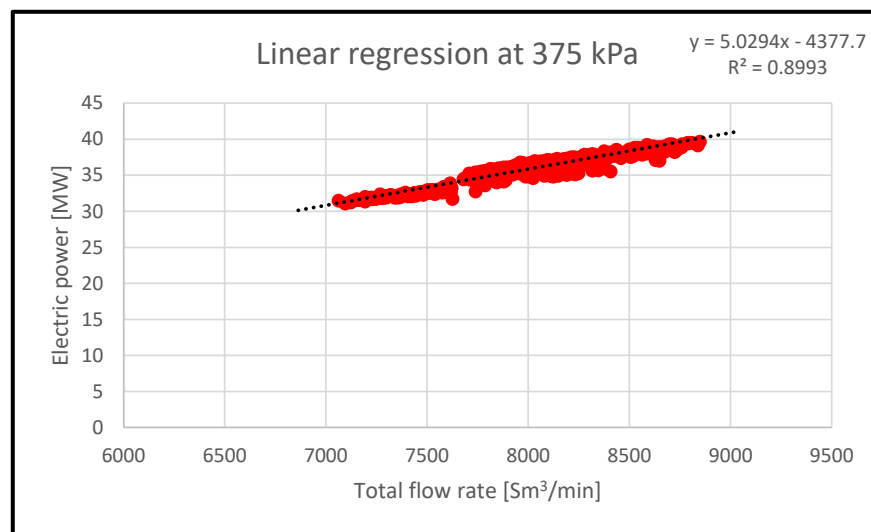


Figure 50: System power linear regression at 375 kPa

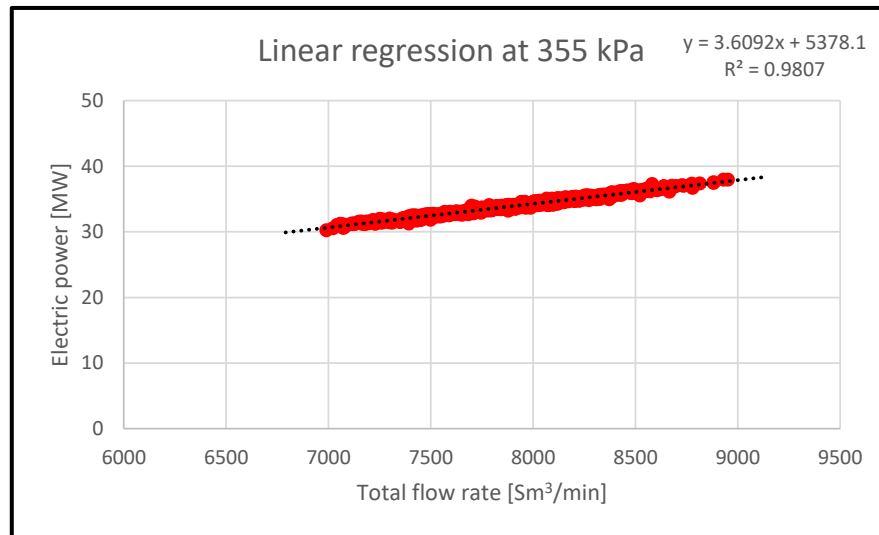


Figure 51: System power linear regression at 355 kPa

In order to calculate the actual average saving that was achieved, the average flow is used to calculate the power consumption at each set point. The average flow is the same as used previously, which is 7 858 Sm³/min. The difference between the two values is the saving that was actually achieved. The results of the calculation are given in Table 11.

Table 11: Linear regression saving validation results

	Power [kW]
Average power consumption at 375 kPa	35 143
Average power consumption at 355 kPa	33 739
Saving due to 20 kPa reduction	1 404

It can be seen that over a long period of time, the implemented strategy provided a saving larger than in the simulation. Therefore, it can be concluded that for the linear regression method, the saving is validated and sustainable in the long term.

Due to other strategies such as leak repair and instrument air optimisation, the load on the HP compressors can be reduced further. Besides the additional saving achieved due to flow reduction, the times of operating at an increased set point will be reduced. This further increases the sustainability of the strategy.

4.5 SUMMARY

The purpose of this chapter was to verify and validate the saving due to the implemented strategy. The saving has been successfully verified using a theoretical calculation. The other criteria identified in the verification criteria were also satisfactorily verified. The

theoretically verified saving was 1.2 MW. This is less than 4% from the 1.25 MW as expected from the simulation.

After verifying the saving, validation was done. This was done using two different methods. The first method used the LP compressor performance map. This method delivered a saving of 1.3 MW. The second method was the drop test combined with a linear regression. These methods delivered a saving of 1.1 MW and 1.4 MW respectively.

In conclusion, the identified strategy delivered a significant energy saving. It was also found to be sustainable through the use of the verification criteria. Other strategies such as leak repair and instrument air optimisation can be used to increase sustainability. These strategies were not within the scope of this study and were, therefore, not considered.

5 CONCLUSION AND RECOMMENDATIONS

5.1 PREAMBLE

The conclusion of the study will be given in this section. It will be determined if the study was a success and the reason therefore will be discussed. After this a recommendation for further research will be given on other possible strategies that could be implemented to further increase the energy saving.

5.2 CONCLUSION OF THE STUDY

The objectives of this study were identified in Chapter 1. The objectives were used to determine if the study was a success. If it could be said that the objectives have been reached, the study could be said to be a success.

In the first chapter general background was given on the components to be considered in the study. That is, the steelmaking industry which includes the ironmaking industry, compressed air systems and energy management. The South African energy situation, which includes the energy crisis in 2008, was also shortly discussed.

From the general information provided in Chapter 1 the need for energy management in the South African ironmaking industry was identified. Ironmaking is an energy intensive industry that consumes large amounts of compressed air. Compressed air is one of the most expensive utilities in all manufacturing plants.

The ironmaking industry was identified as a suitable industry for implementing energy saving strategies. The next step was to identify the objectives of the study. The first two objectives required more detailed background on the ironmaking industry and compressed air systems. From this it was found that ironmaking is a complex and sensitive process. There cannot be any sudden changes in operation since they could result in production loss and large financial impact.

Background on the general components of a compressed air system was also provided. This served as background for the next section in which energy saving strategies were discussed. All compressed air systems have some components in common. For the purpose of this study, more detail was provided on centrifugal compressors.

Centrifugal compressors are commonly used in ironmaking due to the high efficiency and wide range of flow. In ironmaking, a large volume of air is consumed for the purpose of blast

furnace operation. The supply of air needs to be steady and reliable. A small disturbance in the air supply can have a large impact on the operation of the furnace.

In the next objective a range of energy saving strategies on compressed air systems were discussed. The strategies were divided into demand-side and supply-side strategies. On the demand side, the consumer of the compressed air is required to make some changes. These include reducing air wastage, using correct equipment and repairing compressed air leaks to mention a few.

On the supply side, the changes are made at the compressor plant. Compressor operation and control are important for this type of strategy. Through proper operation and control, an energy saving can be achieved without large financial expenses.

Other strategies that may require large financial expenditure are environmental control, system auxiliary equipment and new technology. By controlling variables such as compressor inlet temperature and cleanliness of air, an energy saving can be achieved. The proper selection of suitable auxiliary equipment is also required for minimising system losses. New, more efficient compressors are available, but this requires large financial expenditure.

It can be seen that a wide range of compressed air energy saving strategies is available. In the South African mining industry, many of the strategies have already been implemented with good results. The results from previously implemented strategies have been used in the process of identifying a proper energy saving strategy.

In order to develop an energy saving strategy, the critical parameters in ironmaking had to be identified. In developing the strategy, the critical parameters had to be considered. As discussed previously, ironmaking is a sensitive and complex process. The developed strategy had to be able to achieve energy savings without affecting production.

After identifying the critical parameters and developing a suitable energy saving strategy, an implementation procedure had to be developed. The introduction of Chapter 3 presented and discussed a generic methodology. This generic methodology was applied to an actual system to test the validity and illustrate the process.

The second-last objective was to implement the developed strategy. The implementation process was also discussed in Chapter 3. The strategy was successfully implemented. After implementation the sustainability was tested. Verification and validation were also done.

From verification and validation, it was determined that the strategy was successful in achieving a significant energy saving. The strategy was also found to be sustainable in the long term, although it may require implementing more strategies such as compressed air leak repair.

Maintenance was done on one of the HP compressors several months after the implementation of the energy saving strategy. This included the proper cleaning of all components of the compressor. This significantly increased the efficiency of the compressor. The final result was that the HP compressors were able to always supply the necessary instrument air, although the inlet pressure was decreased. Therefore, the sustainability of the energy savings also increased.

This study can be considered a success since all the objectives have been met. First the necessary background was obtained to develop a suitable energy saving strategy. A strategy was developed, simulated, tested and implemented. The implemented strategy resulted in a significant demand reduction. More improvements can be made to further increase energy efficiency. The possible strategies that were not implemented in this study will be discussed in Section 5.2.

5.3 RECOMMENDATION FOR FURTHER RESEARCH

This study was aimed at achieving compressed air energy savings in the ironmaking industry. No infrastructure changes could be made due to funding not being available. The implemented strategy was developed to have a significant impact with minimal to no expenditure.

It is recommended that the savings achieved from this strategy be used to fund other strategies. This is an effective way of increasing the savings that can be achieved. No additional capital is required to implement new strategies and the system energy efficiency keeps on increasing. Some of the strategies that can be implemented on the system in this study will be discussed in the subsections that follow.

Correctly sized compressor

The system under consideration has five identical compressors with certain limitations due to system constraints. Each of the compressors delivers a flow in the range of 2 000 Sm³/min. When the flow demand is not a factor of 2 000, the compressors need to operate at minimum

load. Sometimes it is required to open the blow-off valves due to the oversupply. This is an inefficient point of operation and should be improved.

Through proper compressor sizing an energy saving can be achieved. By installing a smaller 1 000 Sm³/min compressor, there is potential for approximately 1 MW demand reduction. The presently installed compressors will operate at a higher, more efficient point. The smaller compressor will meet the remaining demand and can also be used as a trimming compressor. Operating the large compressors at constant load will also increase energy efficiency.

This strategy does, however, require a large financial investment. When only considering the saving achieved by this strategy, the payback period is approximately 10 years. Therefore, funding needs to be made available from previously implemented strategies. This will significantly reduce the payback period.

When considering the installation of a new compressor, the system constraint also needs to be considered. The compressors cannot be used to its full potential due to the electric motors not being able to carry the load. A less cost-intensive solution may be to install larger motors on some of the compressors.

Leak repair

Leak repair is a commonly used energy saving strategy that can reduce the demand by up to 50%. In this study, leak repair was not done since the optimisation of the instrument air network was not considered. For the specific system considered, a reduction in instrument air demand will, however, lead to a reduced load on the LP compressors.

In this study it was only determined if the implemented strategy had any negative impact on the system components. In a next study the effect of optimising the entire system needs to be determined. This should maximise the saving that can be achieved.

Leak repair is a typical strategy that has an impact on the system as a whole. By reducing the wastage on the way to the consumer, the load on the HP compressors is reduced. Lower HP compressor demand leads to the load on the LP compressors reducing. In the end, a large saving is achieved on both the HP and LP compressors by reducing wastage.

Proper maintenance

The impact of proper maintenance was seen during the course of this study. After a general overhaul was done on one of the HP compressors, its performance significantly increased.

One of the things done on a general overhaul is the proper cleaning of all the compressor components. The efficiency of the compressor increased, which meant that it could deliver more flow for the same amount of power. This meant that the LP compressors could continuously operate at the lower discharge pressure. This increased the sustainability of the implemented strategy.

Near the end of this study, the inlet filters of the LP compressors suddenly became extremely clogged. This was since the filters reached the end of their life. The clogged filters resulted in a decreased efficiency of the LP compressors. More power was required to deliver the same amount of flow. This could have been prevented through proper preventative maintenance.

Improved inlet air filtering

The quality of the inlet air filter greatly influences the performance of the compressor. The filter must clean the air properly without having a large pressure drop. The clean air is required to reduce the chance of vibration and the need for maintenance. A low pressure drop is required to decrease the amount of power consumed by the compressor.

The initial cost of installing new and improved filters will be significant. However, the manufacturer estimates a 5% reduction in energy consumption. Considering this for the system in this study, the payback period is a few months. A further advantage can be seen in the increased lifetime of the new filter.

In a future study, new filtering technology needs to be investigated. Methods for improving on the filters used presently need to be investigated. Along with this a proper preventative maintenance schedule needs to be developed to ensure continued high efficiency operation.

6 REFERENCES

- [1] G. Bianchi and R. Cipollone, “Theoretical modelling and experimental investigations for the improvement of the mechanical efficiency in sliding vane rotary compressors,” *Applied Energy*, vol. 142, p. 95–107, 2015.
- [2] J. Zetterholm, X. Ji, B. Sundelin and P. M. Martin, “Model development of a blast furnace stove,” *Energy Procedia*, vol. 75, p. 1758–1765, 2015.
- [3] R. Inglesi-Lotz and J. N. Blignaut, “Electricity intensities of the OECD and South Africa: A comparison,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, p. 4491–4499, 2012.
- [4] B. G. Pollet, I. Staffel and K. Adamson, “Current energy landscape in the Republic of South Africa,” *International Journal of Hydrogen Energy*, vol. 40, no. 46, p. 16685–16701, 2015.
- [5] R. Inglesi-Lotz, “The evolution of price elasticity of electricity demand in South Africa: A Kalman filter application,” *Energy Policy*, vol. 39, no. 6, p. 3690–3696, 2011.
- [6] K. O. Rielly and J. Jeswiet, “The need for better energy monitoring within industry,” *Procedia CIRP*, vol. 29, p. 74–79, 2015.
- [7] R. Inglesi-Lotz and J. N. Blignaut, “South Africa’s electricity consumption: A sectoral decomposition analysis,” *Applied Energy*, vol. 88, no. 12, p. 4779–4784, 2011.
- [8] R. Ravinesh, P. Josef, N. Loganathan and R. Devi, “Exploring the role of energy, trade and financial development in explaining economic growth in South Africa: A revisit,” *Renewable and Sustainable Energy Reviews*, vol. 52, p. 1300–1311, 2015.
- [9] H. Fechner, S. Giglmayr, A. C. Brent and P. Gauch, “Utility-scale PV power and energy supply outlook for South Africa in 2015,” *Renewable Energy*, vol. 83, p. 779–785, 2015.
- [10] J. H. Marais, “Analysing DSM opportunities on mine conveyor systems,” Ph.D., North-West University, Potchefstroom, 2007.

-
- [11] V. Strezov, A. Evans and T. Evans, “Defining sustainability indicators of iron and steel production,” *Journal of Cleaner Production*, vol. 51, p. 66–70, 2013.
- [12] S. W. Du, C. P. Yeh, W. H. Chen, C. H. Tsai and J. A. Lucas, “Burning characteristics of pulverized coal within blast furnace raceway at various injection operations and ways of oxygen enrichment,” *Fuel*, vol. 2015, p. 98–106, 2015.
- [13] D. Fu, Y. Chen and C. Q. Zhou, “Mathematical modeling of blast furnace burden distribution with non-uniform descending speed,” *Applied Mathematical Modelling*, vol. 39, no. 23–24, p. 7554–7567, 2015.
- [14] J. Kiventerä, T. Leiviskä, K. Keski-Ruismäki and J. Tanskanen, “Characteristics and settling behaviour of particles from blast furnace flue gas washing,” *Journal of Environmental Management*, vol. 172, p. 162–170, 2016.
- [15] D. Pugh, A. Giles, A. Hopkins, T. O. ’Doherty, A. Griffiths and R. Marsh, “Thermal distributive blast furnace gas characterisation , a steelworks case study,” *Applied Thermal Engineering*, vol. 53, p. 258–365, 2011.
- [16] R. Saidur, N. A. Rahim and M. Hasanuzzaman, “A review on compressed-air energy use and energy savings,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 4, p. 1135–1153, 2010.
- [17] S. Mousavi, S. Kara and B. Kornfeld, “Energy efficiency of compressed air systems,” *Procedia CIRP*, vol. 15, p. 313–318, 2014.
- [18] J. Zachlan and S. Asfour, “A multi-objective approach for determining optimal air compressor location in a manufacturing facility,” *Journal of Manufacturing Systems*, vol. 35, p. 176–190, 2015.
- [19] S. D. Garvey and A. Pimm, “Compressed air energy storage,” Elsevier Inc., 2016.
- [20] D. McAuley, “Compressed air technical guide,” Sustainable Energy Ireland, 2007.
- [21] R. Dindorf, “Estimating potential energy savings in compressed air systems,” *Procedia Engineering*, vol. 39, p. 204–211, 2012.

-
- [22] W. Al-Busaidi and P. Pilidis, “A new method for reliable performance prediction of multi-stage industrial centrifugal compressors based on stage stacking technique: Part 1–existing models evaluation,” *Applied Thermal Engineering*, vol. 98, p. 10–28, 2016.
- [23] M. Geerdes, H. Toxopeus and C. van der Vliet, *Modern Blast Furnace Ironmaking: An Introduction*, Amsterdam: IOS Press, 2009.
- [24] D. Fu, G. Tang, Y. Zhao, J. D’Alessio and C. Q. Zhou, “Modeling of iron ore reactions in blast furnace,” *International Journal of Heat and Mass Transfer*, vol. 103, p. 77–86, 2016.
- [25] L. Shi, G. Zhao, M. Li and X. Ma, “A model for burden distribution and gas flow distribution of bell-less top blast furnace with parallel hoppers,” *Applied Mathematical Modelling*, p. 1–20, 2016.
- [26] A. Sahin and M. Morari, “Optimizing control of hot blast stoves in staggered parallel operation,” in *The International Federation of Automatic Control*, Seoul, Korea, 2008.
- [27] T. Ozbakkaloglu, L. Gu and A. F. Pour, “Normal- and high-strength concretes incorporating air-cooled blast furnace slag coarse aggregates: Effect of slag size and content on the behavior,” *Construction and Building Materials Journal*, vol. 126, p. 138–146, 2016.
- [28] Y. Li, et al, “Environmental impact analysis of blast furnace slag applied to ordinary Portland cement production,” *Journal of Cleaner Production*, vol. 120, p. 221–230, 2016.
- [29] H. Saxén, “Simulation of burden distribution and charging in an ironmaking blast furnace,” in *International Federation of Automatic Control*, 2015.
- [30] J. Liu, Q. Xue, X. She and J. Wang, “Investigation on interface resistance between alternating layers in the upper of blast furnace,” *Powder Technology*, vol. 246, p. 73–81, 2013.
- [31] Y. Li, X. Zhang, J. Zhang, J. Zhou and H. Yan, “Numerical simulation and optimization of pulverized coal injection with enriched oxygen into blast furnace,” *Applied Thermal Engineering*, vol. 67, p. 72–79, 2014.

-
- [32] Z. Zhao, H. Tang, Q. Quan, J. Zhang and S. Shi, “Simulation study on performance of novel oxygen-coal lances for pulverized coal combustion in blast furnace tuyère,” *Procedia Engineering*, vol. 102, p. 1667–1676, 2015.
- [33] W. Al-Busaidi and P. Pilidis, “Modelling of the non-reactive deposits impact on centrifugal compressor aerothermo dynamic performance,” *Engineering Failure Analysis*, vol. 60, p. 57–85, 2016.
- [34] D. P. Xenos, G. M. Kopanos, M. Ciccotti and N. F. Thornhill, “Operational optimization of networks of compressors considering condition-based maintenance,” *Computers and Chemical Engineering*, vol. 84, p. 117–131, 2016.
- [35] E. Larralde and R. Ocampo, “Selection of gas compressors: Part 5,” *World Pumps*, vol. 2014, no. 1, p. 38–42, 2014.
- [36] K. Liang, R. Stone, G. Davies, M. Dadd and P. Bailey, “Modelling and measurement of a moving magnet linear compressor performance,” *Energy*, vol. 66, p. 487–495, 2014.
- [37] Y. Lu, F. Wang, M. Jia and Y. Qi, “Centrifugal compressor fault diagnosis based on qualitative simulation and thermal parameters,” *Mechanical Systems and Signal Processing*, vol. 81, p. 259–273, 2016.
- [38] S. Y. Sung and Y. J. Kim, “Modeling of titanium aluminides turbo-charger casting,” *Intermetallics*, vol. 15, p. 468–474, 2007.
- [39] M. Levesque, D. Millar and J. Paraszczak, “Energy and mining: The home truths,” *Journal of Cleaner Production*, vol. 54, p. 233–255, 2014.
- [40] J. R. Neale and P. J. Kamp, “Compressed air system best practice programmes: What needs to change to secure long-term energy savings for New Zealand?,” *Energy Policy*, vol. 37, no. 9, p. 3400–3408, 2009.
- [41] A. de Coning, “Sustained energy performance on compressed air systems for expanding gold mines,” M.Eng thesis, North-West University, Potchefstroom, 2013.
- [42] P. Eret, “A cost-effective compressed air generation for manufacturing using modified microturbines,” *Applied Thermal Engineering*, vol. 107, p. 311–319, 2016.

- [43] J. I. G. Bredenkamp, “Reconfiguring mining compressed air networks for cost savings,” M.Eng thesis, North-West University, Potchefstroom, 2014.
- [44] M. Budt, D. Wolf, R. Span and J. Yan, “A review on compressed air energy storage: Basic principles, past milestones and recent developments,” *Applied Energy*, vol. 170, p. 250–268, 2016.
- [45] X. Fang, W. Chen, Z. Zhou and Y. Xu, “Empirical models for efficiency and mass flow rate of centrifugal compressors,” *International Journal of Refrigeration*, vol. 41, p. 190–199, 2014.
- [46] E. Larralde and R. Ocampo, “Selection of gas compressors: Part 6,” *World Pumps*, vol. 2014, no. 11, p. 36–41, 2014.
- [47] C. Cilliers, “Benchmarking electricity use of deep-level mines,” Ph.D., North-West University, Potchefstroom, 2016.
- [48] S. G. J. van Niekerk, “Quantification of energy consumption and production drivers in steel manufacturing plants,” M.Eng thesis, North-West University, Potchefstroom, 2016.
- [49] C. J. R. Kriel, “Modernising underground compressed air DSM projects to reduce operating costs,” M.Eng thesis, North-West University, Potchefstroom, 2014.
- [50] J. H. Marais, “An integrated approach to optimise energy consumption of mine compressed air systems,” Ph.D., North-West University, Potchefstroom, 2012.
- [51] F. W. Schroeder, “Energy efficiency opportunities in mine compressed air systems,” M.Eng thesis, North-West University, Potchefstroom, 2009.
- [52] A. T. Sayers, *Hydraulic and Compressible Flow Turbomachines*, London: McGraw-Hill, 1990.
- [53] Velan Inc., “Memoryseal® resilient-seated ball valves,” Velan, Montreal, Canada, 2014.