

Utilising automated control principles to reduce compressor operating costs on mines with limited infrastructure

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ABSTRACT

Title: Utilising automated control principles to reduce compressor operating costs on mines with limited infrastructure

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The mining industry faces severe challenges with increasing operating costs at above-inflation rates, particularly the cost of electricity. Compressed air systems are extensively used on mines, making up roughly 20% of the total power consumption on most sites, while on platinum mines this figure can be as high as 38%. This makes compressed air systems a prominent candidate for the implementation of energy efficiency solutions. Research reveals several popular solutions that can improve the efficiency of compressed air systems. However, these solutions require systems to be outfitted with specialised instrumentation and/or software. Thus, systems that are devoid of the required instrumentation and/or software need to be upgraded before savings can be realised. To address this problem, the fundamental principles behind these strategies were used to develop a solution that could generate savings with existing infrastructure and little to no prior investment.

A need, therefore, existed for a simplified methodology that uses the fundamental principles behind popular compressed air control strategies to achieve energy savings. A methodology was developed and implemented as case studies on two mine compressed air networks. The case studies verified the accuracy of the developed solution and validated the solution results. Implementation produced an average total cost saving of R13.7 million annually at 2022 Eskom rates, which deviated from the expected savings with an error of less than 5%.

This study was successfully implemented on platinum mines where energy efficiency solutions have not yet been established, exceeding the expected target outcomes. It is recommended that this solution be implemented in industry where energy efficiency projects are still in their infancy. Alternatively, the developed methodology can be used on established sites to expand and implement solutions where the needed instrumentation is not yet available.

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MEASUREMENT NOMENCLATURE

Unit	Name/Description
–	Dimensionless
%	Percentage
GWh	Gigawatt-hour
h	Hour
J	Joule
K	Kelvin
kg	Kilogram
kPa	Kilopascal
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
m	Metre
m ³	Cubic metre
Nm ³	Nominal cubic metre
R	South African rand (ZAR)
s	Second

LIST OF SYMBOLS AND UNITS

Symbol	Description	Unit
c	Constant	–
C_p	Molar specific heat	J/kg·K
E	Energy	kWh
$Error\%$	Percentage error	%
g	Pressure	kPa
h	Vertical height/depth	m
k	Specific heat ratio	–
KPI	Resistance to pressurised flow	Nm ³ /kPa·h
$\dot{m}$	Mass flow rate	kg/s
n	Number of moles in gas	–
p	Pressure	kPa
P	Power	kW
$\dot{Q}$	Nominal volumetric flow rate	Nm ³ /h
R	Gas constant	kJ/mol·K
SP	Specific power	kW·h/Nm ³
t	Time	h
T	Temperature	K
V	Volume	m ³
Greek		
Δ	Difference	–
η	Efficiency	–
ρ	Density	kg/m ³

LIST OF ABBREVIATIONS

Abbreviation	Description
ACC	Automated Compressor Control
CS	Compressor Schedule
DCC	Dynamic Compressor Controller
DCS	Dynamic Compressor Selector
GPS	Global Positioning System
GVC	Guide Vane Control
IPMVP	International Performance Measurement and Verification Protocol
ISO	International Organization for Standardization
IT	Information Technology
KPI	Key Performance Indicator
MNC	Manual Network Control
OPC	Open Platform Communication
PLC	Programmable Logic Controller
REMS [®]	Real-time Energy Management System
REMS [®] CM	Real-time Energy Management System – Compressor Manager
SANS	South African National Standards
SCADA	Supervisory Control and Data Acquisition
SP	Specific Power
TOU	Time of Use
VSD	Variable Speed Drive

LIST OF TERMINOLOGY

Term	Description
Autocompression	A phenomenon that occurs in compressed air pipelines that traverse a significant altitude difference where the mass of the air at higher altitude further compresses the air at lower altitude.
Baseload compressor	A compressor that is dedicated to supplying air to the continuous minimum compressed air demand of a system and is thus rarely stopped or controlled dynamically.
Demand-side	The part of a closed system where a commodity is consumed or crosses and exits the system boundary.
Pressure transducer	A device that converts fluid pressure to an electrical signal - also known as a pressure sensor.
Supply-side	The part of a closed system from which a commodity originates or crosses and enters the system boundary.
Trimming compressor	A compressor that can be stopped/started and controlled dynamically to manage the compressed air supply of a system – i.e. not a baseload compressor.
Validation	The process employed to confirm that the solution results addressed the original problem statement.
Verification	The process employed to confirm that the developed solution is accurate and suitable for use.

CHAPTER 1: INTRODUCTION AND LITERATURE

1.1 Energy management on South African mines

1.1.1 Energy in South Africa

1.1.1.1 Demand exceeding supply

The South African electrical grid is under tremendous strain with rolling blackouts, referred to as load-shedding, affecting the entire country as supply fails to meet demand [1]. The cumulative number of hours without power as recorded in days per year were 22 in 2019, 36 in 2020, 49 in 2021, and exceeded 100 days in 2022 with the implementation of stage 6 load-shedding [2]. The meaning of the loadshedding stages is yet to be clearly defined, but roughly indicate the desired load reduction on the grid where Stage 1 indicates a 1 GW reduction, Stage 2 indicates 2 GW, and so on [2]. The deteriorating stability and rising costs of electricity are motivating consumers to look for ways to reduce their grid-tied consumption.

1.1.1.2 Increasing electricity costs

The cost of electricity in South Africa has been rising rapidly since the early 2000s and is a result of several factors such as gross mismanagement, lack of maintenance, and insufficient generation capacity on the grid [1]. Eskom is South Africa's primary electricity generation and transmission company and is almost solely responsible for the country's electricity supply. Annual Eskom tariff adjustments have been increasing at above-inflation rates for more than a decade as shown by the compounded trends in Figure 1-1.

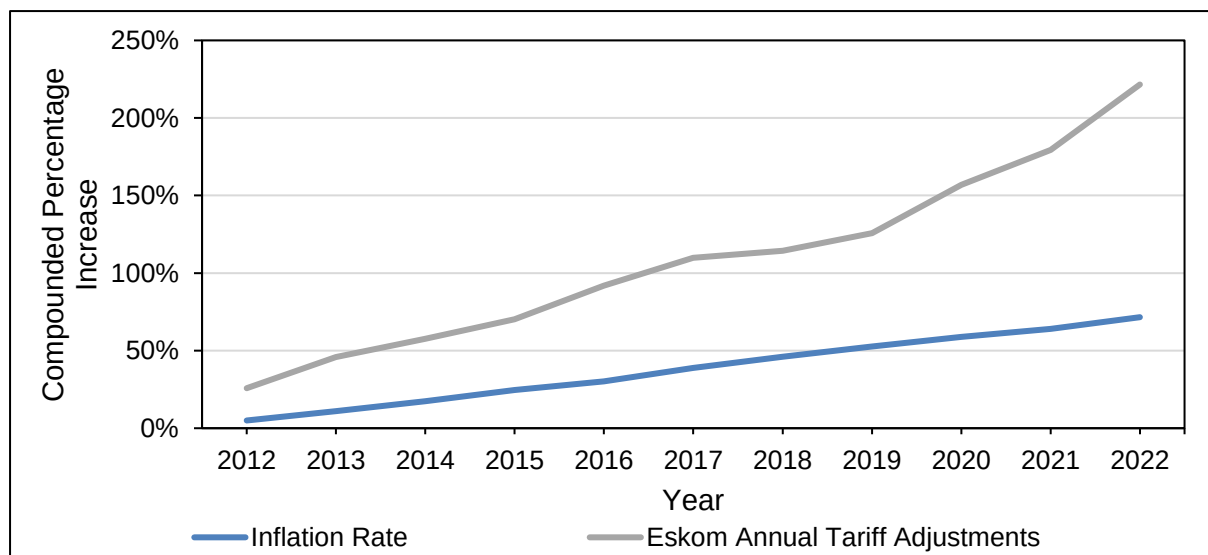


Figure 1-1: South African inflation rates and Eskom annual tariff adjustments (adapted from [3] and [4])

It was announced in early January 2023 that the Eskom tariffs would increase by a further 18.7% for the new year while inflation was at 7.7% [5]. This has pushed many consumers to either reduce their energy consumption or pursue independent generation options to supplement their energy needs.

1.1.1.3 Energy consumption of the South African mining sector

The mining industry is a significant energy consumer in South Africa, ranking as the third largest annual electrical consuming sector according to Eskom's records [1]. During peak load periods, the South African mining and industrial sectors use roughly 60% of the peak power demand [6]. Furthermore, the industrial generation of compressed air is estimated to use about 9% of this peak demand, leaving 51% of the peak demand for other mining and industrial activities [7]. Data shows that the South African mining industry has consistently accounted for around 15% of the country's total annual electrical energy consumption since 2015 [1]. The largest and second largest annual electrical energy consumers are national distributors (municipalities) at 45% and the industrial sector at 25% respectively [1].

1.1.1.4 Utilities and schedules

Understanding Eskom's rates and schedules is key when applying load-shifting or other cost saving strategies. Eskom uses time-of-use (TOU) schedules to structure industrial electricity costs [7]. The Eskom TOU summer schedule for South Africa is shown in Figure 1-2.

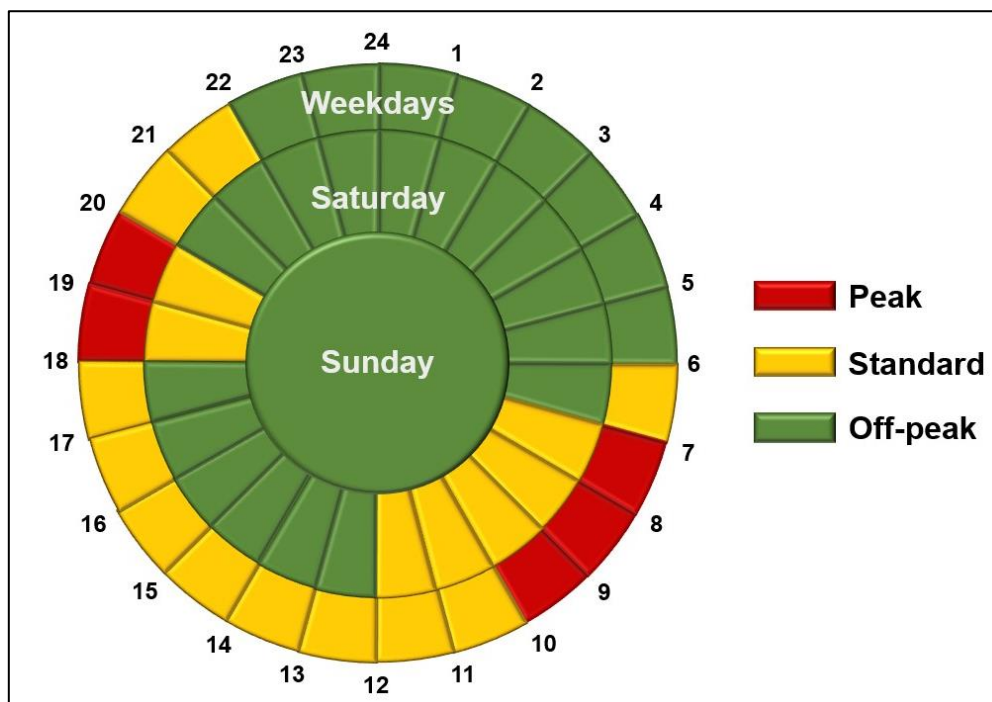


Figure 1-2: Eskom summer Megaflex TOU periods (adapted from [8])

Eskom's Megaflex billing structure is used by most mines, and Figure 1-2 shows the TOU periods used. The different periods are assigned different electricity tariffs, with the most expensive being the peak period, the cheapest the off-peak period, and the standard period in between [7]. These tariff periods are used to motivate larger consumers to reduce their consumption during peak periods when the grid is most constrained. Load-shifting is a common method used for this purpose and shifts the work activity times so that high consumption activities take place outside peak periods [9].

1.1.2 Energy management in the mining environment

1.1.2.1 Background to energy management

The goal of energy management is to reduce wasted energy and use every unit of energy as effectively as possible [10]–[15]. As energy costs have been far less significant in the past, detailed monitoring thereof has not been common practice. More recent increases in energy costs have since caused the mining industry to recognise gaps in their energy systems' effectiveness [16]. For the most part, the industry has become increasingly aware and focused on energy management [17].

With increased environmental awareness, not only are energy costs imposed on the mining industry but also environmental costs with mounting pressure to focus on energy efficiency. This further motivates the need for energy management to curb an array of costs. Negligence thereof may impose more strain on industries with the resulting increased environmental costs [10], [16], [18], [19]. Carbon emission is an environmental factor that imposes such costs and is a direct result of energy use [20]. Improving energy management requires technical adaptations to improve the efficiency of a process or simply better management of resources and important parameters to reduce risks imposed on safety and production [21].

As mentioned, there are two areas that industry has become aware of, namely the gap in energy management and the gap in energy efficiency [16]. The gap in energy management refers to the lack of proper management of operational resources such as schedules, parameters, and people [16]. The gap in energy efficiency pertains to the energy efficiency difference between actual and theoretical values [16]. The actual and theoretical values are the result of real-world implementation and the system design, respectively.

With the numerous interactions in a single system, the management of energy and efficiency becomes significantly more complicated. The implementation of more energy efficient technologies is often hindered by the complexity in the interactions of processes in the system [16]. The limitations, processes, and available utilities are often unique to each industrial site.

The solution should simplify the management of the most important parameters within the limitations of the industrial system.

1.1.2.2 Implementing energy management

The implementation of an energy management strategy requires the energy manager to have a sufficient level of competency in the management of the technical, economical, and logistical aspects of the project [17]. Collaboration with the necessary personnel and managers is required to implement the procedures detailing how to execute the monitoring and control of the strategies [22]. These strategies should additionally aim to mitigate risks to safety, production, and equipment while curbing energy consumption [22].

The energy manager should set out the control of these strategies to be orderly and sustainable [16]. Key performance indicators (KPIs) and benchmarks obtained from system analysis should be used to assist in controlling the strategy [23]. Such parameters, data, and further information form part of the control and should be gathered neatly to ensure sustainability [24].

Documentation of tasks and procedures to communicate with management is crucial for managing strategies, their organisation, and logistics. This forms the foundation from which communication and effective training can propagate as the traceability, organisation, and relevance of the strategy are fixed [17].

1.1.2.3 Difficulties in energy management

Energy-governing factors such as energy content, consumers, energy sources, distribution of energy, production, process layout, and their management directly influence energy management [24]. Many important parameters are generated from these factors, increasing the management complexity and data volumes. Data volumes are further inflated by the requirement for permanent process monitoring. The management burden grows with these inflating data volumes [25]. Furthermore, such systems are not yet fully independent of human intervention, maintaining some level of human error and presents one of the most vexatious difficulties therein.

The use of KPIs enables the management of energy-governing factors; however, comparing and defining KPIs are complicated [10]. With the variety of processes – each having its own set of requirements and limitations and hundreds of possible combinations – the process becomes increasingly tedious [10]. The challenge resides with the ability to take these interconnected characteristics and generate relatable KPIs that can be widely understood [10].

Reporting is key for monitoring the performance and progress of an energy management strategy [26]. Moreover, the use of a well-designed report that presents relevant data is instrumental in data-driven decision-making. The data resolution and analysis required by the target users must be known as it influences the data volumes and thus the complexity of the analysis [27].

1.1.2.4 Identifying the greatest energy consumers

The primary purpose of an energy audit or system analysis is to identify influential inefficiencies and the greatest energy consumers [16]. It is found that compressors are one of the largest electricity consumers in the mining industry. Roughly 10% of the total industrial electricity consumption is attributed to compressed air generation in Australia and some European countries [28]–[30]. The same 10% are used for compressed air generation in the United States as well [28], [31]. This indicates that one of the most expensive energy sources around the world is in fact compressed air [28].

Similar observations are seen in the South African mining industry. Compressors are responsible for around 20% of the total electricity consumption on the industry’s gold mines [7]. Some platinum mines have recorded percentages of up to 38% as seen in Figure 1-3.

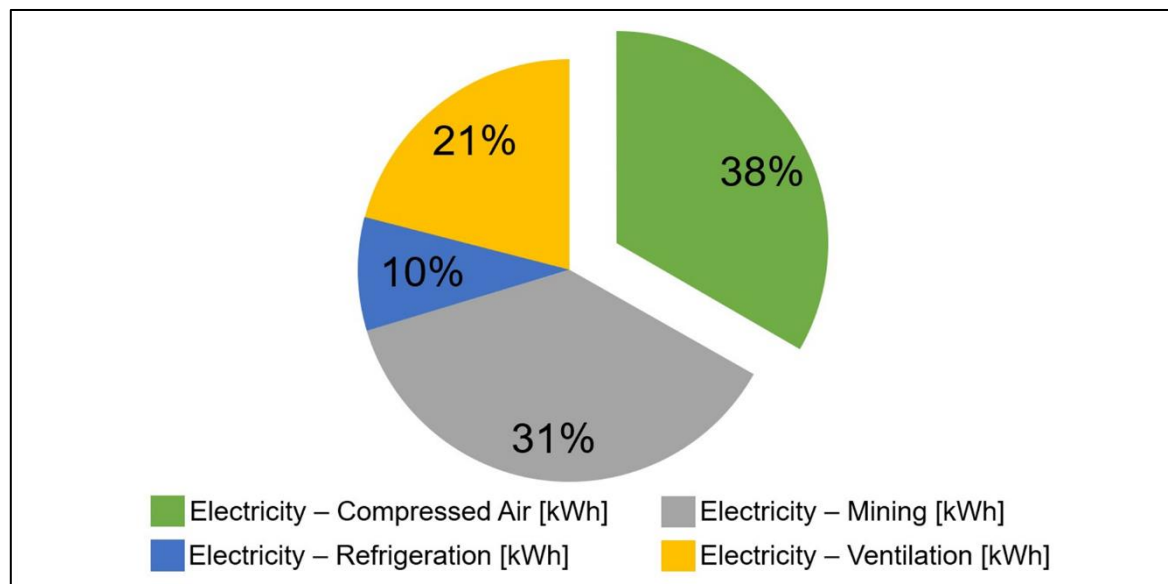


Figure 1-3: Platinum mine high-level electrical distribution (adapted from [21])

It is clear that reducing compressed air consumption in the mining industry is instrumental in reducing electricity consumption and increasing cost savings.

1.2 Mine compressed air systems

1.2.1 Preamble

All compressed air systems start at the compressor. Work is done by the capacity of a compressor, while the rate at which work is done is influenced by the discharge pressure [32]. The compressors used on mines are significantly larger than the familiar units often seen in workshops. The capacities of mine compressors commonly range from 0.5 MW to 15 MW, and most fall within the range of 2 MW to 5 MW. When a 5 MW compressor is started, the power consumption is roughly equivalent to that of more than 400 homes during peak hours. It is no mystery why mine compressed air systems have such a significant impact on the local energy consumption.

1.2.2 Supply-side operations and compressors

Industrial mining compressors come in various types, all with different advantages and disadvantages. Commonly used dynamic compressors are either axial compressors or the more popular centrifugal compressors as shown in Figure 1-4.

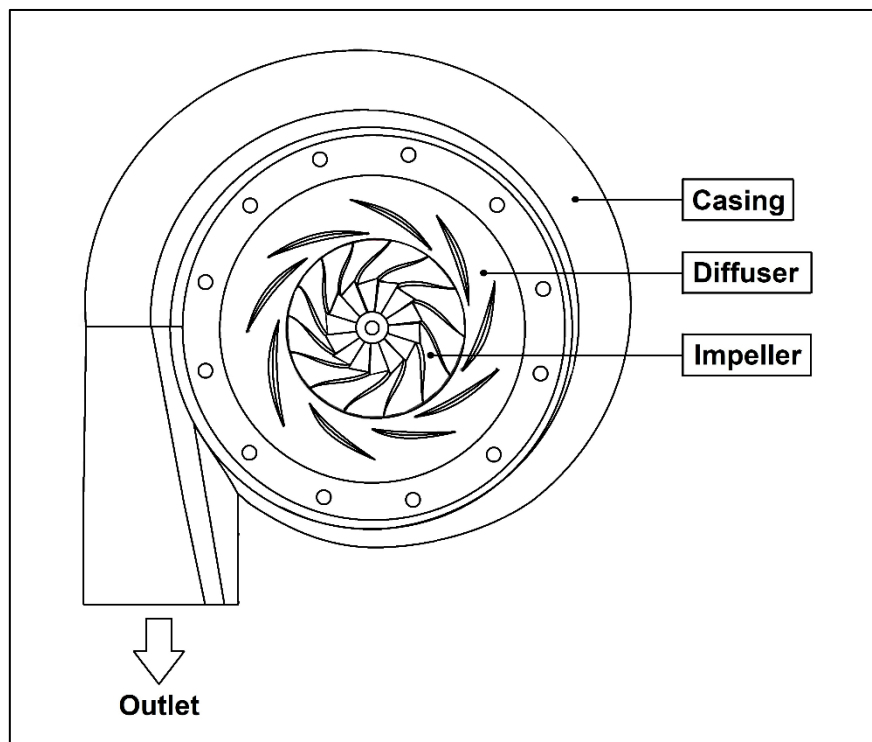


Figure 1-4: Centrifugal compressor basic internal structure (adapted from [33])

1.2.2.1 Centrifugal compressors

Compressed air on mines is most commonly supplied by centrifugal compressors. Centrifugal compressors have few advantages (adapted from [28]):

- They use guide vanes to control the delivery pressure by limiting the flow;
- They have fewer frictional parts than positive displacement compressors;
- They outperform equal capacity positive displacement compressors in terms of airflow; and
- They are comparatively energy efficient.

Furthermore, centrifugal compressors are popular due to their low vibration, simplicity, and large capacity [34]. However, the pressure ratios of dynamic compressors are far lower than the high-pressure ratios that characterise positive discharge compressors [9]. For this reason, multiple centrifugal compressors are used in series with the air discharged from the preceding compressor flowing through an intercooler and into the impeller of the next. Each compressor forms a stage that applies further compression to build up a useful overall pressure ratio for industrial applications [35]. These multi-stage compressors are normally driven by a single motor through gearing with a large bull gear connecting and driving the different stages.

A centrifugal compressor pressurises air by converting the driving motor energy into kinetic energy through the rotational movement of the impeller. The impeller applies a centrifugal force or outward pressure on the air, which converts most of the energy into kinetic energy as the air gains velocity in the compressor [36]. As the air is discharged through the diffuser (by Bernoulli's principle where pressure is inversely proportional to velocity squared), it loses kinetic energy and thus velocity while it gains potential energy in the form of pressure [36]. As the flow is continuous through centrifugal compressors, they are known as dynamic machines [36].

Constant speed electric motors are the most commonly used driving motor on centrifugal compressors. Variable speed drives (VSD) feature on newer compressors and allow the compressor to run at different speeds, which make it more efficient [35]. As fossil fuel motors are less efficient than electric motors, the latter is preferred [37].

1.2.2.2 Risks of surge

Compressor maintenance is expensive, and measures must be taken to reduce the risk of damage, such as avoiding surge. Surge [38]–[40] occurs in areas with low flow supply. It causes extreme vibrations that could damage the compressor while generating excessive

noise as well. When a compressor is cut back and the flow rate decreased, the discharge pressure also decreases. Flow travels from a high-pressure region to a low-pressure region. If the pressure downstream remains high, the flow direction could flip and force air into the compressor. The pressure in the compressor builds up and exceeds the downstream pressure that dropped when the flow direction flipped, causing the flow to flip back again. The flow flipping back and forth results in an oscillating cycle with major vibrational stresses imposed on the compressor internals. These stresses cause major wear on parts such as impeller thrust bearings and mounts.

1.2.2.3 *Blow-off*

The primary purpose of blow-off valves [41] is to prevent surge, and thus they are also known as anti-surge valves. As described in the previous section, surge occurs when the downstream pressure exceeds the compressor discharge pressure. For this reason, the blow-off valve opens to release excess downstream air into the atmosphere. This reduces the downstream pressure and allows flow to pass through the compressor as desired.

1.2.2.4 *Guide vane control*

Inlet guide vanes [35], [42] are commonly used to manage compressor discharge pressure according to a target or set point by adjusting the velocity of the air relative to the impeller as the vanes adjust the angle at which the air enters the impeller. Less energy is transferred to the fluid with increased velocity relative to the impeller. The exit velocity drops as a result. The guide vanes are synchronised and their angle is adjusted by turning of the ring or yoke assembly. An example of compressor inlet guide vanes is shown in Figure 1-5.

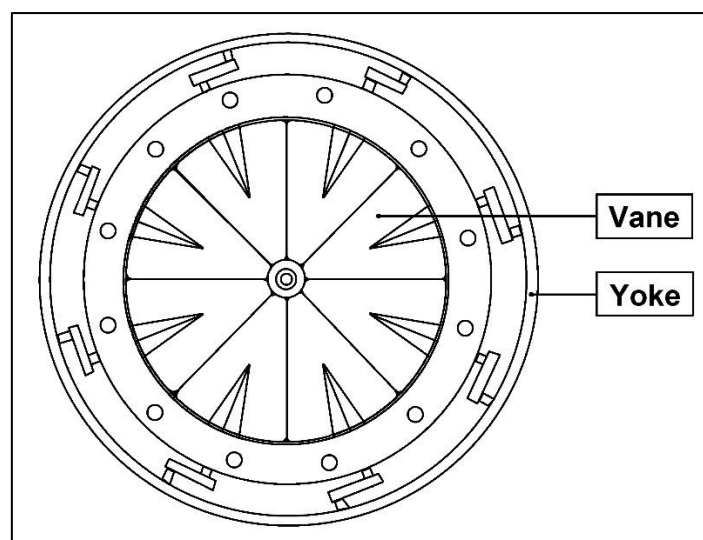


Figure 1-5: Compressor inlet guide vanes basic structure [original to author]

The guide vane control [35] alters the mechanical efficiency of the compressor. Depending on the guide vanes and compressor, the maximum efficiency is normally observed between 80% and 100% open guide vanes. The maximum energy consumption is often at 100% open guide vanes.

1.2.3 Mine compressed air networks

The supply-side compressors are connected to the demand-side compressed air consumers via a compressed air network, commonly constructed of steel pipes. The layout of the site determines the type of compressed air network, whether a stand-alone or ring-feed network.

1.2.3.1 Stand-alone networks

Stand-alone systems [9] generally have a single-source feed directly to their single or sometimes paired consumers. Single consumers are most often shafts, whereas when looking at paired consumers, we may consider the case where a processing plant also requires compressed air. An example of a single and paired consumer stand-alone system is shown in Figure 1-6.

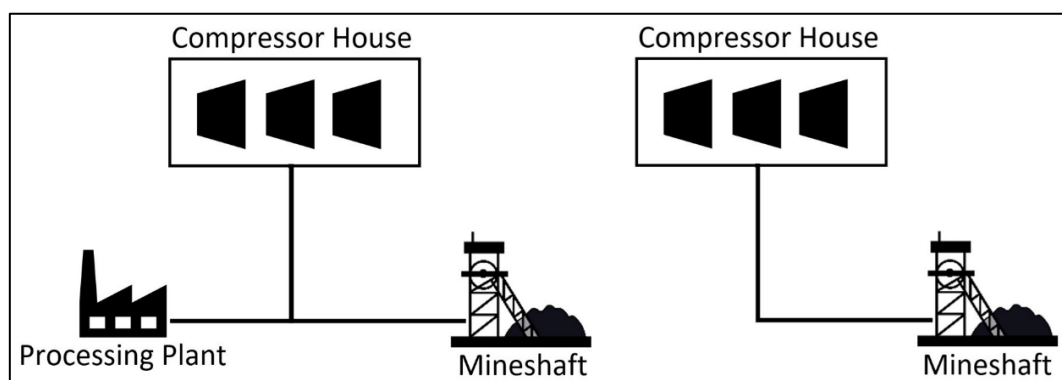


Figure 1-6: Stand-alone compressed air systems [original to author]

1.2.3.2 Ring-feed networks

Ring-feed systems, also known as compressed air rings, have a variety of sources feeding several different consumers. An example of a compressed air ring is shown in Figure 1-7.

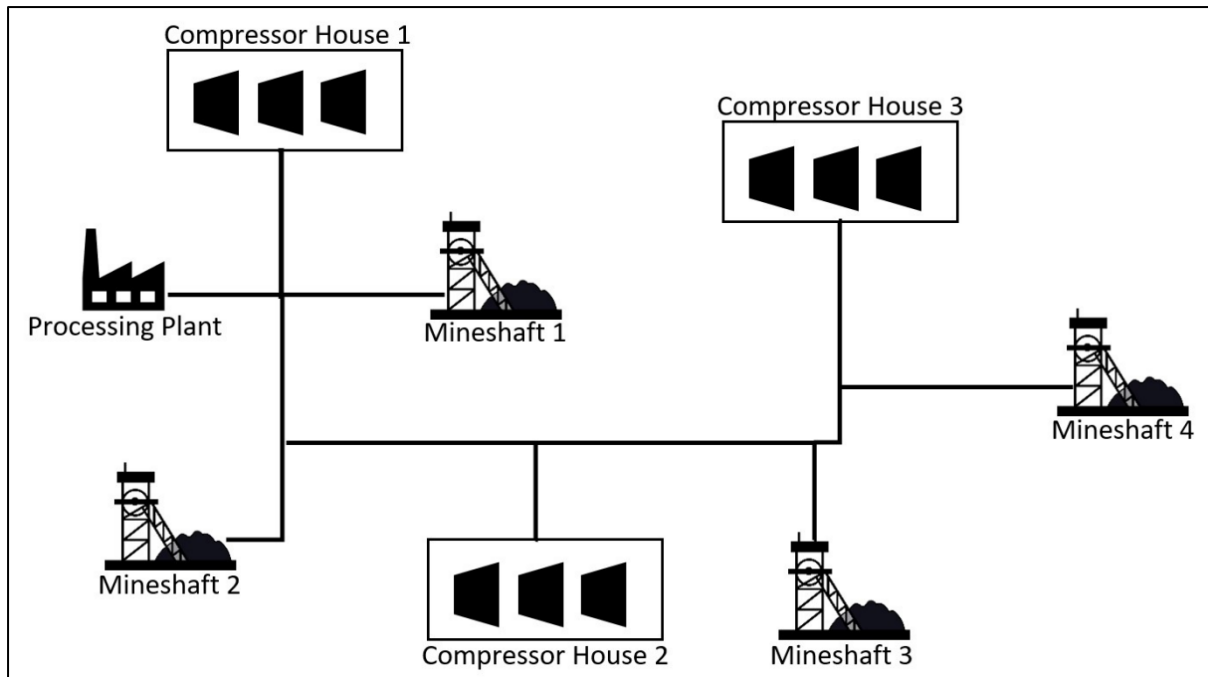


Figure 1-7: Ring-feed compressed air system [original to author]

Ring-feed compressed air [9] networks are the most popular arrangements used on mines due to the decentralisation of supply. This allows for various control options and the ability to supply consumers while some sections of the ring experience downtime. However, network pressures do vary due to consumer connection points and their changing demand, adding exponential complexity to the system and its control. Furthermore, the large scale of such a system leads to pressure losses over long pipelines and greater maintenance costs.

1.2.4 Demand-side operations

Identifying consumers and their usage schedules will enable the implementation of control infrastructure and schedules. At mining sites, underground compressed air consumption makes up the majority of the demand and thus underground consumers are highlighted first [9].

1.2.4.1 Rock drills

During the drilling period of the schedule, pneumatic drills are used to drill into the rockface where the blasting charges are placed in the holes. During this time, the drills are the primary consumers. Rock drills consume compressed air at flows between 200 Nm³/h and 1 500 Nm³/h and at pressures between 400 kPa and 620 kPa [43].

1.2.4.2 Venturi blowers

Temperatures underground can become uncomfortably high, thus venturi blowers are sometimes used during all shifts outside the blasting period to cool working areas and circulate fresh air. Venturi blowers consume compressed air at flows between 70 Nm³/h and 330 Nm³/h and at pressures between 350 kPa and 620 kPa [43].

1.2.4.3 Mechanical ore loaders

After the blasting period and during cleaning, the mined ore and rock are loaded into loading boxes with mechanical ore loaders. These loaders are the primary consumers during this period and function best at a high fixed pressure with constant airflow. Loaders consume compressed air at a flow of 1 000 Nm³/h and at a pressure of 450 kPa [41].

1.2.4.4 Diamond drills

Development on mining levels is carried out with diamond drills and is not part of the production shifts. This allows development to take place during any time in the schedule when most convenient but can make the demand unpredictable in some cases. However, development is unlikely to take place during the blasting period. Diamond drills consume compressed air at a flow of 500 Nm³/h and at a pressure of 500 kPa [43].

1.2.4.5 Refuge bays

Although refuge bays are sometimes continuous consumers of compressed air, in some mines they only consume air when opened during an emergency. These refuge bays are charged with positive atmospheric pressure to keep harmful gases out and provide a safe chamber for workers in the event of an emergency. Refuge bays consume compressed air at a flow of 5 Nm³/h per occupant and at pressures between 200 kPa and 300 kPa [43].

1.2.4.6 Rock breakers

As the name suggests, rock breakers break up large rocks to make the hoisting of ore more manageable during the cleaning period. Rock breakers consume compressed air at a flow of 1 000 Nm³/h and at a pressure of 450 kPa [43].

1.2.4.7 Loading boxes

Loading boxes operate in the cleaning period and are actuated pneumatically to load the mined rock and ore into the skips that carry the load to surface. Loading boxes consume compressed air at flows between 20 Nm³/h and 500 Nm³/h and at pressures between 350 kPa and 600 kPa [41].

1.2.4.8 Blow pipes

The biggest wastage of compressed air underground are open-ended air lines that workers use in poorly ventilated areas. These lines are not authorised installations, very difficult to track, and have severe negative effects on compressed air pressure and demand. However, there are some installations used for cleaning (sweeping) of development or mining areas during periods outside blasting. Open-ended pipes consume compressed air at flows between 720 Nm³/h and 5 700 Nm³/h and at pressures between 100 kPa and 650 kPa [43].

1.2.4.9 Pneumatic cylinders

Pneumatic cylinders are used extensively on systems that handle ore to open and close different chutes and doors during cleaning. Pneumatic cylinders consume compressed air at flows between 2 Nm³/h and 500 Nm³/h and at pressures between 350 kPa and 600 kPa [43].

1.2.4.10 Agitators

Agitation is used in water dams to keep sediment from settling and promote agitated tank leaching. These systems may not be active on all sites but are active throughout the schedule on active sites. Agitators consume compressed air at a flow of 1 700 Nm³/h and at a pressure of 400 kPa [43].

1.2.4.11 Other instrumentation

A variety of other instrumentation such as pneumatically actuated control valves also consume a small amount of compressed air. These systems normally need to be available and active at all times. Actuators consume compressed air at very low flows and at pressures between 350 kPa and 600 kPa [43].

1.2.4.12 Autocompression

The information in Section 1.2.4 thus far can be used to determine the demand-side operational requirements; however, when doing so, it is important to take the effects of autocompression into account. As the compressed air pipelines descend vertically in a shaft, the compressed air itself is further compressed under its own weight, which is known as autocompression [44]. Thus, the pressures at the various levels increase from the surface pressure which is directly proportional to the depth of the respective level [44]. This increase in pressure is calculated with Equation 1-1.

Equation 1-1: Pressure increase due to autocompression (adapted from [45])

$\Delta p = \rho gh$			
Δp	=	<i>Pressure increase</i>	[kPa]
ρ	=	<i>Density of air</i>	[kg/m ³]
g	=	<i>Gravitational acceleration</i>	[m/s ²]
h	=	<i>Depth below surface</i>	[m]

However, this formula is only accurate for a static system where the compressed air is not flowing. There are formulae that can be used for dynamic systems, but they may be futile as compressed air flows in a shaft are unpredictable and change on a daily basis.

The distribution of compressed air flow in a shaft can often completely nullify the effects of autocompression on some levels and have no effect on others. Thus, Equation 1-1 simply approximates what to expect as the best-case scenario. In most cases, consulting the shaft engineer or taking measurements may provide more valuable insight into the specific shaft dynamics.

1.2.5 Compressed air supply control strategies

Supply-side management refers to the control and monitoring of the machines and rates of supply of some utility. In the case of compressed air, some examples of optimisation strategies fall under (adapted from [42]):

- Reduction of system pressures;
- Multiple compressor control implementation; and
- Compressor delivery control optimisation.

1.2.5.1 *Reduction of system pressures – manual network control*

Manual network control and pressure targets: To reduce system pressures, one control strategy is highlighted, namely using manual network control and pressure targets. Pressure targets may take the form of set points. Depending on the measured pressure in relation to the target, a compressor either has to be started or stopped. This results in what is called network control [35], which refers to the management of compressor starts and stops on a compressed air network. The use of such control reduces electricity consumption. Although this type of control is purely a manual process, when supplemented with fixed compressor schedules or a range of automated systems such as dynamic compressor selection (DCS), these automated variations of network control fall under the multiple compressor control strategies discussed below.

1.2.5.2 *Multiple compressor control implementation – compressor schedules*

Automation of compressor control: Automation of control is ideal as it eliminates human error and makes the system predictable. There are software control applications that perform network control and manages the air pressure according to set points by controlling the number of running compressors. An energy management system is such a program [46]. The pressure set points are digital target pressures that, when exceeded sufficiently, cause the program to turn off a compressor. When the pressure is sufficiently below target, a compressor is started [35]. However, automated control is not always possible depending on the limitations of the specific system or mining environment. The extent of automation further varies greatly between systems.

Compressor priorities [9]: Mining compressed air networks normally comprise multiple compressors, each with their own characteristics such as efficiency and capacity. The efficiency of each compressor must be determined to develop the compressor priorities for the control. Should there be an existing automated compressor control system that automates

network control, programming the developed priorities into this system should be simple. Essentially, the priorities should be set up so that the available compressors are started according to efficiency while giving preference to the more efficient compressors.

Often limitations hinder the implementation of such a system – primarily the lack of automated compressor control. In such a case, an adjusted strategy [9] is to install a monitoring system that identifies the ideal compressor stops and starts and informs the operator performing manual network control of the desired action. The compressed air network target air pressure can be maintained effectively by using the operator feedback strategy [9]. This type of system – whether automated or not – is referred to as a DCS controller. In this study, it falls under the compressor schedule grouping of strategies.

1.2.5.3 Compressor delivery control optimisation – guide vane control

Automated inlet guide vane control: There are multiple compressor delivery control strategies, but inlet guide vane control [44] is used most regularly on mining sites. Guide vane control throttles the inlet flow of a compressor to control the discharge pressure according to a pressure set point. This allows improved control of the network pressures. Section 1.2.2.4 covered guide vane control in more detail.

1.2.6 Compressed air demand control strategies

Demand-side air consumption can be controlled underground or on surface [47]. Two demand-side control examples are air pressure and flow control, and air wastage management.

1.2.6.1 Air pressure and flow control – valve control

Automated valve control: Pressure and flow are commonly controlled through an automated pressure control valve installed in the main air line on the shaft surface. A valve maintains the downstream pressure according to a pressure set point, which then controls the passing airflow [44].

1.2.6.2 Air wastage management – air leak management

Manual air leak management: Compressed air leaks can result in up to 70% of the total compressed air being lost in systems that severely lack proper maintenance [48]. These leaks can cause a 20% to 30% pressure drop in work area's air lines [9]. Regular audits and maintenance of the underground pipe networks is therefore crucial to manage the impact of leaks.

1.3 Existing automated control strategies

1.3.1 Preamble

Solutions to similar compressed air control problems have been developed before, and it is important to study and learn from such literature. Section 1.3 of this document contains the technical literature study of previous projects and studies that implemented automated control strategies on mines. The literature is reviewed to highlight the specific strategies used, whether the study was successful, and what difficulties or shortcomings were experienced. This is followed by the development of a problem statement.

From the information gathered, the automated control strategies are prioritised and the fundamental principles behind each strategy identified. These automated control principles can be used to identify and develop alternative strategies that produce the desired results.

1.3.2 Demand-side management improvement

In this section, automated demand-side strategies such as those discussed in Section 1.2.6 are further investigated in literature. Any available savings achieved by each study are reported at 2022 Eskom rates.

1.3.2.1 Valve control

As discussed in Section 1.2.5, a control valve is installed in the main air line at a consumer. The valve position is adjusted to control the airflow through it to maintain the downstream pressure at a specified pressure set point. The reduction in flow demand has a direct impact on the flow supply and thus energy used.

Joubert [9] considered a control strategy using four pressure control valves to manage the air delivered to the shafts during the Eskom evening peak period. Due to a lack of required infrastructure, these control valves had to be repaired and new valves installed. The study achieved a reported load reduction of 8.3 MW in the Eskom evening periods. This resulted in savings of R8.3 million per annum with a significant payback period of 20 months. The total compressor capacity on the mine was 38.7 MW from thirteen machines of varying capacities.

Deyssel [49] considered a control strategy using eight pressure control valves to reduce the downstream pressures. The use of compressor control allowed more effective management of compressed air and the realisation of savings. However, the required infrastructure was incomplete, and repairs and new installations had to be carried out. The study achieved a peak average load reduction of 4.4 MW over the implementation period and savings of

R6.3 million per annum with a significant payback period of 25 months. The total compressor capacity on the mine was 23.0 MW from five machines of varying capacities.

In 2016, Fouché [44] utilised valve control on five underground levels of a mineshaft to manage the upstream and downstream pressures. The valves were used to manage and prioritise the level pressures in emergency situations. Furthermore, to produce savings, the valves were controlled during the morning changeover period (04:15–06:15) to reduce level consumption and elevate upstream pressures. The use of guide vane control on the compressors maintained stable upstream pressures and saved energy when the valves tried to elevate the upstream pressures. However, faulty infrastructure was encountered and had to be repaired before valve control could be implemented. The study achieved an average reported load reduction of 0.07 MW per day period, which equated to savings of R1.0 million per annum. The total compressor capacity on the mine was 19.2 MW from four 4.8 MW machines.

Valve control was successfully implemented in all the studies discussed. However, each study encountered limited infrastructure that first had to be repaired before implementation. Nonetheless, each study achieved significant annual monetary savings while having an average daily load reduction in the range of 0.3% to 1.8% of their system capacities.

For valve control it was observed and recorded that the following data and infrastructure requirements were either identified for the respective solutions or became apparent during implementation. These common requirements were identified across the respective studies. The data and infrastructure requirements for this strategy are summarised in Table 1-1.

Table 1-1: Valve control implementation requirements

Infrastructure	Data
- Compressed air pipelines - Control valve - Valve position sensor - Flow meters - Pressure transducers - Electric power meters - Valve programmable logic controller (PLC) - Communication network - Historian/database - Supervisory control and data acquisition (SCADA) - Centralised control room	- Consumer pressure requirement - Consumer post-valve pressure - Consumer pre-valve pressure - Consumer valve position - Consumer flow - Compressor discharge flows - Compressors electric power

These requirements will serve to identify whether the strategy can be implemented on a system without later encountering data or infrastructure limitations.

1.3.3 Supply-side management improvement

In this section, automated supply-side strategies such as those discussed in Section 1.2.5 are further investigated in literature. Any available savings achieved by each study are reported at 2022 Eskom rates.

1.3.3.1 Guide vane control

Guide vane control requires pressure set points to be specified according to the maximum pressure requirements of the ring [49]. This allows the guide vanes to throttle the flow into the compressor to control the discharge pressure according to the set points. More detail on guide vane control is covered in Section 1.2.2.4.

Deyssel [49] used guide vane control as the compressor control strategy on five compressors to better manage compressed air and obtain savings while implementing valve control. The study states that the implementation cost of a full compressor controller is estimated to be R1.7 million per compressor, but the mine already had a similar system in place. The system was in need of costly upgrades in active surge control, surge curve plotting, and independent set point and inlet guide vane control.

When Fouché [44] used guide vane control, it was not only to respond to the morning changeover demand variations but also to reduce and manage the pressures during the evening peak period. A compressor set point schedule was developed and implemented. Guide vane control in the evening peak periods achieved an additional average reported load reduction of 0.07 MW over a day period, which equated to R1.0 million per annum. The total compressor capacity on the mine was 19.2 MW from four 4.8 MW machines.

Hassan *et al.* [50] used guide vane control to manage supply pressures outside of the drilling period. Several tests were carried out to determine the potential impact of the solution. However, implementation did not take place due to a severe lack of infrastructure. The theoretical impact of the guide vane control had an expected average reported load reduction of 1.1 MW over a day period, which equated to R10.4 million per annum. The total compressor capacity on the mine was 24.7 MW from five machines of varying capacities. As implementation did not take place the power reduction of 4.6% of the system capacity and any reported savings were purely theoretical. Therefore, these values will be disregarded.

Guide vane control was successfully implemented in all the studies discussed. However, each study encountered limited infrastructure that first had to be repaired before full implementation could take place. Nonetheless, each study achieved significant annual monetary savings while having average daily energy savings in the range of 0.3% to 1.6% of their system capacities.

For guide vane control it was observed and recorded that the following data and infrastructure requirements were either identified for the respective solutions or became apparent during implementation. These common requirements were identified across the respective studies. The data and infrastructure requirements for this strategy are summarised in Table 1-2.

Table 1-2: Guide vane control implementation requirements

Infrastructure	Data
• Valve control;** and ○ Compressed air pipelines ○ Trimming compressors ○ Compressor subsystems ○ Inlet guide vanes ○ Guide vanes position sensor ○ Blow-off valve ○ Blow-off valve position sensor ○ Flow meters ○ Pressure transducers ○ Electric power meters ○ Subsystem sensors ○ Compressor controller ○ Subsystem controllers* ○ Guide vanes PLC ○ Communication network ○ Historian/database ○ SCADA ○ Centralised control room	• Valve control;** and ○ Consumer pressure requirement ○ Consumer-side pressure ○ Consumer flow ○ Compressor inlet guide vane position ○ Compressor blow-off valve position ○ Compressor discharge pressure ○ After-cooler discharge pressure ○ Compressor discharge flow ○ Compressor running status ○ Compressor electric power ○ Compressor alarm status ○ Compressor trip status ○ Compressor start sequence status ○ Compressor stop sequence status

(*) – Dependent on the system and only necessary when applicable; (**) – Optional and recommended but not a strict requirement

These requirements will serve to identify whether the strategy can be implemented on a system without later encountering data or infrastructure limitations.

1.3.3.2 Compressor schedules

Compressor schedules prioritise compressors according to their efficiencies, capacities, and the demand that needs to be met. In some cases, these schedules are fixed and developed to guide operations but most are automated through DCS controllers.

Joubert [9] considered a control strategy to optimise the compressor schedule during the Eskom evening peak period. The schedule optimisation was made possible on two mines due to the installation of control valves and other infrastructure to reduce the shaft's air demand. Due to mechanical limitations on the compressors of the second mine, the target savings were not realised. The project achieved a reported load reduction of 3.1 MW in the Eskom evening periods. The resulting monetary saving was R3.1 million per annum with a payback period of 36 months. However, the payback period was extended to 40 months due to extra energy use in the expensive morning peak period. The author recommended compressor automation on the first mine but did not implement it due to the extensive cost involved to repair and update the limited infrastructure within the limited budget for the project. The total compressor capacity on the mine was 20.4 MW from five machines of varying capacities.

The control strategy considered by Van Heerden [35] developed a DCS that adjusted compressor priorities and their guide vane set points according to changing demands. The project encountered several difficulties such as inaccurate or faulty instrumentation, the lack of control valves at the shafts, and existing policies that hindered the valve control. The project further showed the DCS to be unstable and unreliable due to instrumentation issues. Thus, the system was not implemented to fully automate the compressor control but rather used as an advisory tool or indicator. The project achieved an average reported load reduction of 1.8 MW over a day period, which equated to R8.2 million per annum. The total compressor capacity on the mine was 34.0 MW from nine machines of varying capacities.

The use of compressor schedules was successfully implemented in all the studies discussed. However, each study encountered limited infrastructure that first had to be repaired before implementation could take place. Nonetheless, each study achieved significant annual monetary savings while having average daily energy savings in the range of 0.6% to 5.3% of their system capacities.

For compressor schedules it was observed and recorded that the following data and infrastructure requirements were either identified for the respective solutions or became apparent during implementation. These common requirements were identified across the respective studies. The data and infrastructure requirements for this strategy are summarised in Table 1-3.

Table 1-3: Compressor schedules implementation requirements

Infrastructure	Data
• Valve control;** • Guide vane control;** and ○ Compressed air pipelines ○ Trimming compressors ○ Compressor subsystems ○ Blow-off valve ○ Blow-off valve position sensor ○ Flow meters ○ Pressure transducers ○ Electric power meters ○ Subsystem sensors ○ Compressor controller ○ Subsystem controllers* ○ Communication network ○ Historian/database ○ SCADA ○ Centralised control room ○ External simulation software* ○ Control panel system* ○ Monitoring system**	• Valve control;** • Guide vane control;** and ○ Consumer pressure requirement ○ Consumer-side pressure ○ Consumer flow ○ Compressor discharge pressure ○ After-cooler discharge pressure ○ Compressor discharge flow ○ Compressor running status ○ Compressor loaded status ○ Compressor electric power ○ Compressor ready to start status ○ Compressor alarm status ○ Compressor trip status ○ Compressor start sequence status ○ Compressor stop sequence status

(*) – Dependent on the system and only necessary when applicable; (**) – Optional and recommended but not a strict requirement

These requirements will serve to identify whether the strategy can be implemented on a system without later encountering data or infrastructure limitations.

1.3.3.3 Automation of compressed air control

Today, automated control systems are the pinnacle of practical and widespread system optimisation – with the exception of machine learning and its increasing popularity. These systems are a collection of the possible individual control strategies that have been discussed and are implemented as a single control system. The complexity of these systems varies and is heavily dependent on the available infrastructure.

The year following the completion of the study by Van Heerden [35], a continuation of the project was undertaken. Van Heerden [51] developed a dynamic compressor controller (DCC) in a new study to expand on and address the shortcomings of the DCS that had been developed. The DCC considered factors such as compressor locations and efficiencies which the DCS did not. Unfortunately, the project could not be implemented due to constraints from the client's side but was simulated to predict the potential savings. Two case studies were

used: the first was a platinum mine (where the DCS had been implemented) and the second was a gold mine with no pre-existing automated control. The infrastructure issues encountered on the first case study were rectified since the study of the previous year. However, the second case study had some limitations in its infrastructure that needed to be addressed before the implementation of the DCC would be possible.

The first case study had less potential savings due to the existing DCS project with an average reported potential load reduction of 0.02 MW over a day period with a cost saving of R1.3 million per annum. The second case study had three different scenarios with the maximum average reported potential load reduction of 3.6 MW over a day period with a cost saving of R36.3 million per annum in an ideal scenario. The total compressor capacity on the first case study mine was 34.0 MW from nine machines of varying capacities. The total compressor capacity on the second case study mine was 44.3 MW from seven machines of varying capacities. As this DCC only automated the supply-side, this type of solution is referred to as automated compressor control throughout this study.

The solution Jonker [52] implemented on a gold mine has similarities to that of Van Heerden but with some significant advancements. The study covered the development of what the author called a DCS but with far more advanced capabilities. The developed solution is what can be described as a wholistic compressed air network controller. Not only did the controller prioritise and control the compressors, but it also controlled the demand-side control valves with simulation and forecasting. The use of integrated simulation and accounting for flow and pressure losses across the system made this possible. Some infrastructure limitations were encountered, but workarounds were developed with the appropriate assumptions. The optimised compressed air control obtained the majority of its savings during the evening peak period. A total average reported load reduction of 0.6 MW over a day period was achieved, which equates to R7.0 million per annum. The total compressor capacity on the mine was 61.1 MW from seven machines of varying capacities. As this DCS automated both the supply- and demand-side, this type of solution is referred to as automated compressed air control throughout this study.

Automated control was successfully implemented or evaluated in all the studies discussed. However, each study encountered limited infrastructure that first had to be repaired before full implementation could take place. Nonetheless, each study achieved significant annual monetary savings while having average daily energy savings in the range of 0.05% to 8.1% of their system capacities.

For automation of compressed air control, it was observed and recorded that the following data and infrastructure requirements were either identified for the respective solutions or became apparent during implementation. These common requirements were identified across the respective studies. The data and infrastructure requirements for this strategy are summarised in Table 1-4.

Table 1-4: Automated compressed air control implementation requirements

Infrastructure	Data
• Valve control;* • Guide vane control; • Compressor schedules; and ○ Control panel system.	• Valve control;* • Guide vane control; and • Compressor schedules.

(*) – Dependent on the system and only necessary when applicable; (**) – Optional and recommended but not a strict requirement

These requirements will serve to identify whether the strategy can be implemented on a system without later encountering data or infrastructure limitations.

1.3.4 Control and monitoring systems

1.3.4.1 Background to current control and monitoring systems

Compressors are normally controlled in one of two ways: at the compressor itself or from a central control network. When controlled directly, the PLC is accessed at the compressor. Should the compressor have more advanced automation, central remote control is possible. This same practice applies to control valves installed at compressed air consumers to manage the air supplied. The valves can either be controlled locally or remotely depending on the available infrastructure [9].

Considering the compressors, the delivery flow and pressure of the compressor are measured by the installed instrumentation in each case and sent to the control [53]. The feedback creates a closed-loop control circuit [53]. The use of a remote point on a central control network enlarges the control loop. The measured data is relayed back to the central controller along with the compressor availability and running status. Thereafter, the data informs the controller decisions within a set of control parameters as to which compressors to run [9].

All incoming data for a central control network first enters the data manager/processor where an open platform communication (OPC) connection handles all communication between the network and the SCADA [35]. Furthermore, the OPC stores the data in a database that can be accessed and managed via an OPC data access or historical data access server, referred

to as the historian. Connecting to a SCADA system with an OPC is standard practice and will be assumed to be the case for the developed solution.

The central controller may have advanced control software on highly automated sites, while on sites with low-level automation there may be a human operator. The flow of communication over a central control network is shown in Figure 1-8.

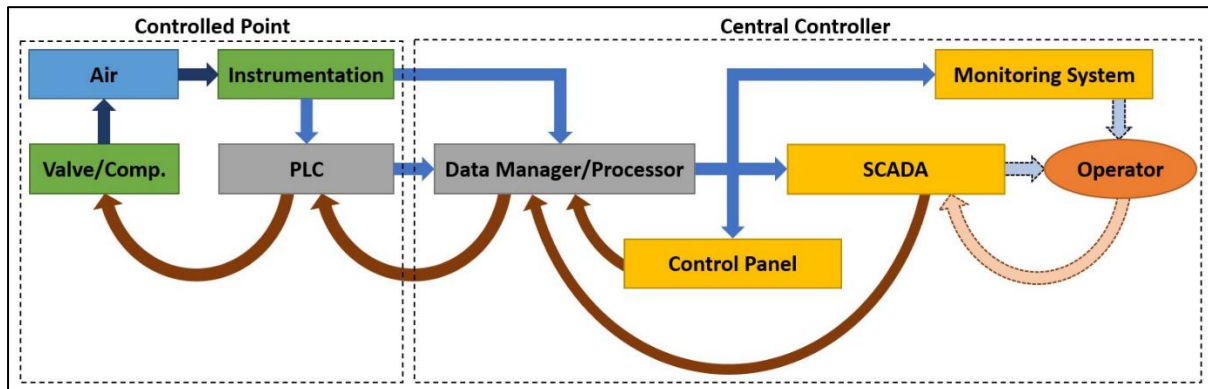


Figure 1-8: Central control networks flow diagram [original to author]

The three primary control and monitoring systems commonly seen on the central controller side are a monitoring system, a SCADA, and a control panel. All three are not always present, but a SCADA is almost always present on its own with one or both of the other two systems.

The type of monitoring and/or control system used is highly dependent on the level of site automation. Highly automated sites may use control panel systems to automate operations significantly, whereas highly or moderately automated sites that experience some reliability issues may opt for a monitoring system. Sites with low-level automation may only have a SCADA system that is controlled by a human operator.

1.3.4.2 SCADA systems from literature

A SCADA collects and makes all the data from the PLCs and instrumentation on the communication network available to the operator. It further allows an operator to input commands and control machinery on the network. The instrumentation and standards specific to a mine dictate the communication protocols used. An example of a SCADA display showing the compressor set points of a case study mine is shown in Figure 1-9.

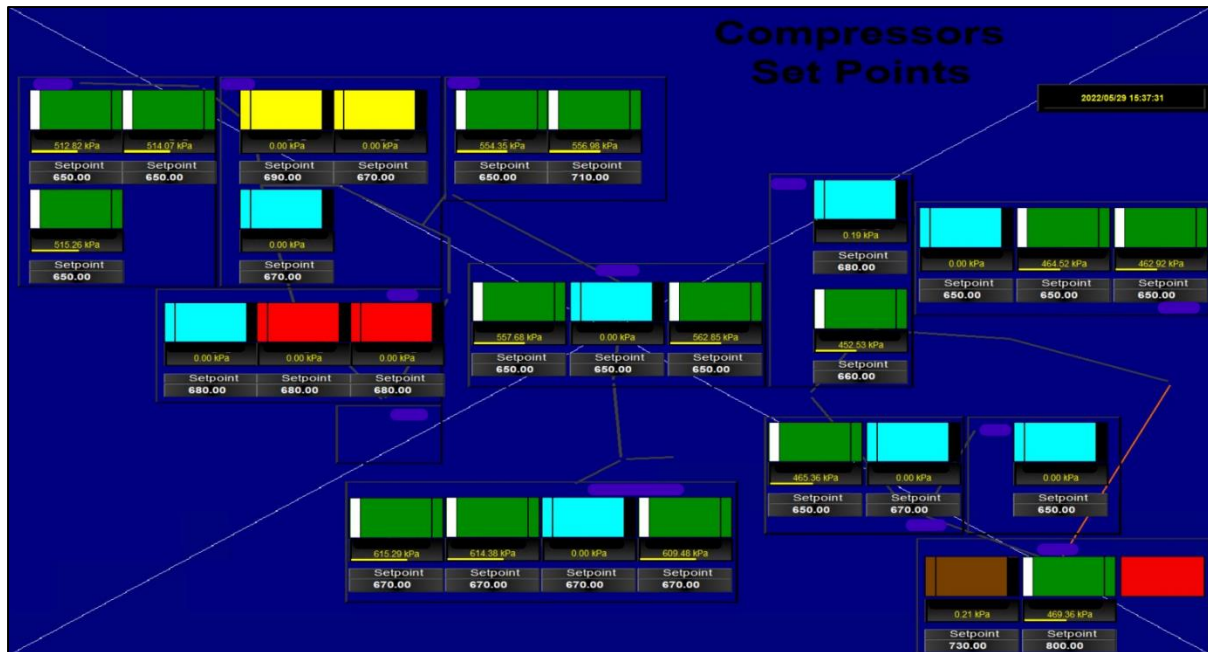


Figure 1-9: SCADA compressor set points display example [original to study]

The SCADA shown indicates five different parameters for each compressor. The central colour of the unit indicates its status, the white bar indicates its guide vane position, the black bar indicates the blow-off valve position, the small text just below the unit indicates the discharge pressure, and the bottom text indicates the compressor set point. The compressor set point can be selected and adjusted on the display.

A SCADA is almost always used for mine compressed air systems, and each is unique to the specific mine. All the studies investigated encountered a SCADA system on their respective mines each with varying complexity.

1.3.4.3 Monitoring systems from literature

Automation of control is not always possible as some systems have limitations that prevent a control system from directly engaging and controlling said system. Rather than leaving automated control altogether, the same control system can be used as a monitoring system. The monitoring system can process the control input data and provide outputs as feedback for a human operator to implement. Such monitoring systems vary significantly in their complexity, but their purpose is all the same: process input data to provide control outputs or guidelines for operator use.

Joubert [9] used REMS[®] CM (Real-time Energy Management System – Compressor Manager) to interpret and monitor real-time data and system parameters to inform the control operators' actions. The system output did not directly control the compressors but simply

assisted in the monitoring and evaluating of the system data and parameters to prompt the operator. The REMS software was underutilised and limited to monitoring in this case as the client had concerns regarding reliability due to infrastructure issues. The REMS software has the potential to function as a control panel. Due to the software being an inhouse product, the cost was not specified in the study. However, it was made clear that such software is costly and takes significant time to implement on any system.

An example of the REMS platform is shown in Figure 1-10.

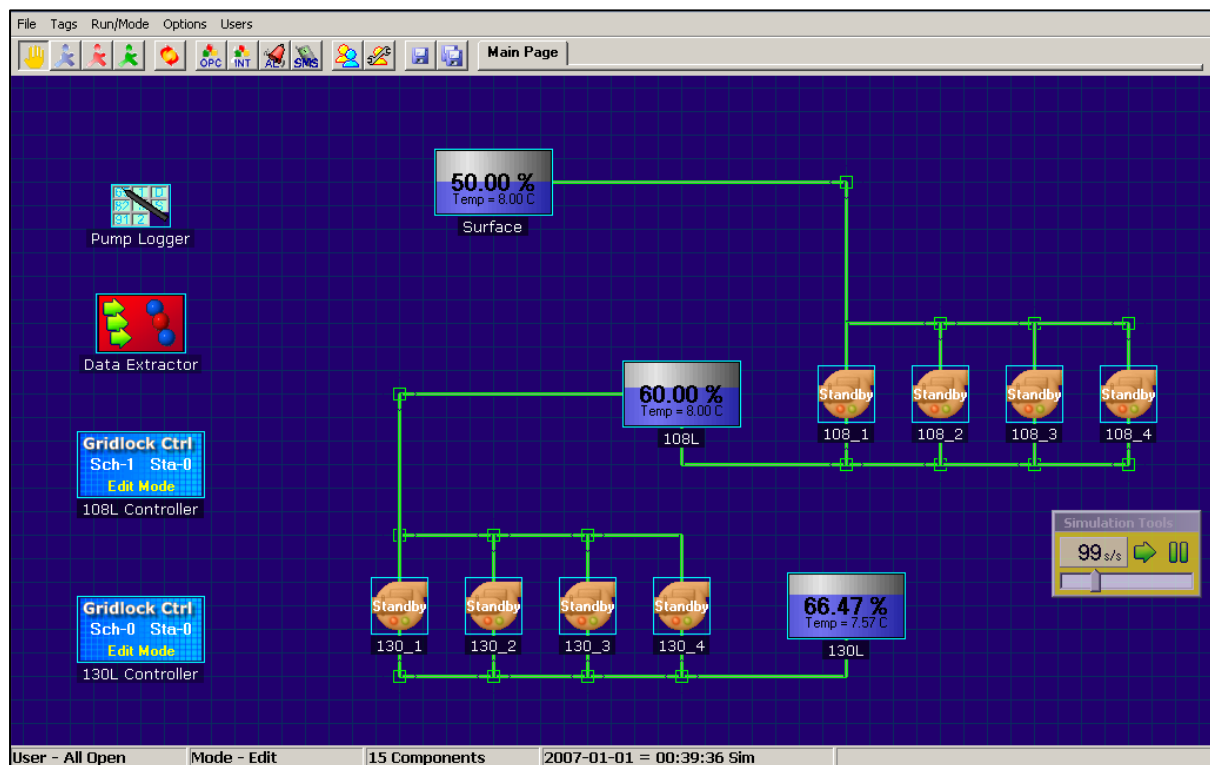


Figure 1-10: Overview of REMS platform (originally from [54])

Monitoring systems are an effective way of implementing the desired control when system limitations hinder full automation.

1.3.4.4 Control panel systems from literature

In the context of this study, control panel systems are platforms that allow full automation of control. When active, control panel can process input data and deliver outputs directly to the system that is to be controlled. These control systems adapt to changes and conditions of the system to optimise the operation thereof.

Unlike Joubert [9], Jonker [52] used the same REMS platform to develop a fully automated control system. The use of REMS and an integrated simulation made it possible to produce an impressive control system. Again, the cost implications of this system were not discussed.

Deyssel [49] used the Simatic WinCC Advanced control panel interface and 128 PowerTag software to manage incoming data and control the valves. As the mine already had a SCADA in place, there was no need to use the WinCC Professional software that would include a full SCADA functionality. The total cost of the two software packages was over R85 000 at the time. Due to limited infrastructure, hardware for a dedicated data server was also commissioned and installed and came to over R350 000 at the time of the study.

An example of the WinCC control panel is shown in Figure 1-11.



Figure 1-11: Siemens HMI control panels with WinCC (originally from [55])

Control panel systems are used to automate the control of a system. Its ability to rapidly process input data to determine the optimum outputs reduces reaction times and improves efficiency for manually controlled systems.

1.3.5 Automated control principles

This section investigates and discusses the control principles behind popular automated control strategies.

1.3.5.1 Valve control

Control valves [9], [44], [45], [49] as discussed in Section 1.3.2.1 can be programmed for flow control or pressure control. Pressure control is more common as the valves are capable of adapting to changing flow demands while providing safe and useful pressures to shaft equipment. This is much like electricity being supplied to a consumer's home and appliances at a controlled and useful voltage with an adaptable current.

A pressure control valve restricts flow by varying the size of the opening of the valve. This causes a pressure drop over the valve that can be controlled. The control principle is thus pressure – specifically post-valve pressure.

1.3.5.2 Guide vane control

Guide vane control [44], [49], [56] as discussed in Section 1.3.3.1, much like valve control, can be programmed for flow control or pressure control. Again, pressure control is more common as guide vanes are capable of adapting to changing flow demands while providing safe and useful pressures the same way control valves do. The control principle is thus also pressure; however, in this case, it controls all pressures downstream of the compressors.

Traditional guide vanes are normally fixed and designed to optimise the airflow into the compressor according to the turbine's geometries. However, control guide vanes can change their pitch or angle at which they allow air to enter the compressor. This changes the compressor's performance characteristics or more commonly simply throttles or restricts the flow through the compressor. Much like control valves, common guide vane control restricts flow by varying the angle and the opening of the vanes. This reduces the amount of air the compressor can compress and results in lower discharge pressures. Additionally, the restricted vane opening causes a pressure drop over the guide vanes and thus supplies the compressor with a reduced intake pressure from which to compress the air. The technical aspects of this type of control were discussed in Section 1.2.2.4.

1.3.5.3 Compressor schedules

Compressor schedules [9], [35] as discussed in Section 1.3.3.2 predominantly focus on efficiency and flow control. However, since this is done to supply useful pressures to consumers, the primary control principles are efficiency, flow, and pressure. The controlled regions are efficiency and flow at the compressors and, much like guide vane control, they control all pressures downstream of the compressors.

There are a variety of different approaches to compressor schedules. The most common approach evaluates the distribution of demand flows and pressures of the system. It selects compressors that are able to match that distribution, and it supplies the air needed to meet those demands. When compressor efficiencies are known, many take it a step further by selecting the most efficient compressors that meet the requirements. The selection of compressors is repeated at specific time intervals throughout the day to follow the changing demands. The analysis and selection are normally done with tools such as simulation or forecasting. If reliable live data is available, it can be done in real time.

1.3.5.4 Automation of compressed air control

Automation of compressed air control [51], [52] as discussed in Section 1.3.3.3 is an amalgamation of different control strategies and can thus come in one of two forms. However, the primary control principles remain efficiency, flow, and pressure control for both. The controlled regions are efficiency and flow at the compressors and all pressures downstream of the compressors.

There are two primary approaches to the automation of compressed air control. Automated compressor control only controls supply-side systems such as compressor schedules and guide vanes to meet the demands as controlled by a separate valve control system. However, some reach as far as the demand-side. These automated compressed air control systems control both supply- and demand-side systems to have wholistic control of the entire compressed air system. As this control is a collection of other strategies, it is dependent on the principles of those strategies.

1.3.5.5 Summary of principles

The automated control principles discussed above are summarised in the Table 1-5.

Table 1-5: Summary of automated control principles

Strategies	Principles
Valve control	Pressure control (shaft)
Guide vane control	Pressure control (network)
Compressor schedules	- Pressure control (network) - Flow control - Compressor efficiency
Automation of compressed air control	- Pressure control (network) - Flow control - Compressor efficiency

The principles identified for each strategy can be used to match compatible alternative strategies to implement in order to achieve the same goals.

1.4 Problem statement and overview

1.4.1 Problem statement and objectives

1.4.1.1 Problem statement

South Africa's rapidly increasing electricity costs present a significant challenge for the local mining industry and encourages companies to reduce their energy demand to curb these costs. A significant proportion of the energy demand for the industrial sector is used to generate compressed air. The generation and use of compressed air is awfully inefficient and widely practised in the mining industry. The significant associated costs make it the ideal candidate for the potential implementation of energy efficiency solutions.

The literature review in Section 1.3 provided several popular solutions for improving the efficiency of mine compressed air systems. The most effective and commonly used are automated strategies that either control supply-side or demand-side systems to improve and manage the compressed air pressures or flows. These improvements result in reduced supply and demand and minimises oversupply, which in turn result in energy savings.

However, although these strategies are proven and robust, they require mining systems to be outfitted with specialised instrumentation or software. Thus, systems devoid of the required instrumentation need upgrade their systems before savings can be realised. None of the studies considered in Section 1.3 specifically investigated solutions that could be implemented

within the limitations of an existing system to generate savings with little to no capital expenditure. To address this problem, the fundamental principles behind these popular and proven strategies are used to develop and identify alternative solutions that require little to no prior investment to achieve similar goals and generate savings.

A need therefore exists for a methodology to identify, implement, and evaluate the control strategies possible within the capabilities of the existing limited infrastructure on a mine compressed air network, based on the fundamental principles behind popular automated control solutions, to produce energy savings.

1.4.1.2 Study objectives

The primary objective of this study is to develop a methodology to identify, implement, and evaluate control strategies compatible with existing mine compressed air infrastructure, guided by control principles from popular automated control to produce energy savings. To do this, the following objectives have to be achieved:

- Develop a methodology to identify, implement, and evaluate control strategies with the purpose of:
 - Avoiding directly effecting any change to the existing infrastructure, thus avoiding the associated capital cost thereof.
 - Yielding energy savings.
- Implement and verify the developed methodology.

1.4.2 Dissertation overview

1.4.2.1 Chapter 1: Introduction

The study was introduced by providing an overview of energy cost and the management thereof in the South African mining industry. Detail pertaining to mining compressed air systems was presented. Thereafter, a study of existing popular control strategies provided insight into their advantages and drawbacks. The key control principles these strategies are built upon were identified. Considering the difficulties experienced in the mining industry and the drawbacks of popular control strategies, a need was identified, and a problem statement presented. Finally, the study objectives were defined.

1.4.2.2 Chapter 2: Development of solution

To provide a solution to the problem statement developed in the previous chapter, this chapter outlines the process of developing the methodology. This methodology uses automated

control principles to implement an energy cost savings strategy within the limitations of existing mine infrastructure. It starts by analysing a system, whereafter it determines the operational requirements, develops the implementation strategy, and lastly details the verification and validation process.

1.4.2.3 Chapter 3: Implementation and results

This chapter shows the methodology implementation process followed on two mine compressed air networks and the individual results obtained. On each case study mine, once the suitable strategies are identified, the control targets and methods are determined. The theoretical energy improvement is calculated, the implementation proceeds, and the actual energy improvement is determined. The energy improvement is used to verify the theoretical model of the solution methodology. Finally, the results are discussed, the solution validated, and the value of the developed solution expanded upon in the context of the South African mining sector.

1.4.2.4 Chapter 4: Conclusion

The study is concluded with a summary of the document that highlights important details and results. Some of the limitations encountered are addressed, and recommendations for future work are made. The document closure brings the study to its fulfilment.

CHAPTER 2: DEVELOPMENT OF SOLUTION

2.1 Preamble

A theoretical methodology is developed in Chapter 2 to identify, implement, and evaluate possible control strategies compatible with the existing infrastructure on a mine compressed air system. The four-part structure of the methodology was adapted from structures observed in literature as well as the guidelines provided in the South African National Standards (SANS) and International Organization for Standardization (ISO) 50001 standards [57]. The developed methodology is summarised in Figure 2-1.

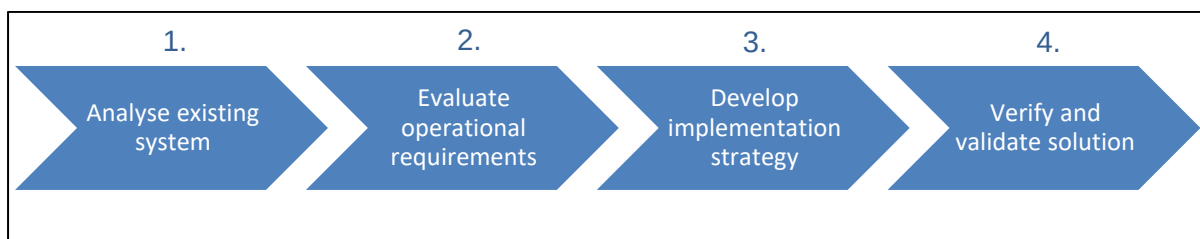


Figure 2-1: Summary of solution methodology developed in Chapter 2

First the system is analysed and the existing infrastructure investigated. The physical compressed air system is first broken down followed by the control system, and all the important available infrastructure and operational schedules identified.

Second, the key control principles are identified and the possible control strategies determined from the respective operational requirements. Furthermore, a method to obtain the control principle targets is shown.

Third, once the strategy to be used has been identified, the implementation strategy is developed. How to determine the required control and monitoring for the strategy is shown and both the control and monitoring implementation strategies are developed.

Fourth and finally, the solution verification methods are determined. The process of developing baselines according to International Performance Measurement and Verification Protocol (IPMVP) guidelines and how the baselines are managed are explained. Thereafter, the verification methods are discussed.

2.2 Analyse system

2.2.1 Determine compressed air system layout and operation

2.2.1.1 Compressed air system layout

This section investigates the system layout and focuses on the network arrangement, the locations of the suppliers, and that of the consumers.

Network

In order to design or implement any form of control, information regarding the compressed air network is required first. The network type, as discussed in Section 1.2.3, influences all operational and control aspects of the system. However, ring-feed networks are the more complex and most commonly used systems. Therefore, this study uses a ring-feed network as the standard system for the solution design where necessary, although the use of the same method on a stand-alone system is possible.

Further information such as pipe diameters, lengths, and bends is required for more advanced solutions. Solutions where detailed calculations or simulations are carried out use pipeline geometries to calculate flows and pressures throughout the network [52]. Should complete layout drawings not be available, GPS plotting or images can be used to determine the layout along with physical measurements of the pipe sizes [41]. Unfortunately, this is often the case as layout drawings are rarely complete and up to date due to frequent changes to the compressed air network.

Suppliers

The installed supply capacity of the compressors determines the maximum demand the system can supply. The distribution of the suppliers determines how the supply is used to meet the demand. Knowing the individual compressor capacities and locations is therefore critical for developing an energy management strategy. Collecting information such as the compressor location, type, electrical capacity, and flow supply capacity is key [51], [52]. For more advanced solutions, parameters such as compressor efficiency is required. If the compressor efficiencies are not available, it can be calculated with Equation 2-1.

Equation 2-1: Compressor efficiency (adapted from [56])

$$\eta_{comp} = \frac{\dot{m} C_p T_{in} \left(\left(\frac{p_{out}}{p_{in}} \right)^{\frac{k-1}{k}} - 1 \right)}{P}$$

η_{comp}	=	Compressor efficiency	[-]
$\dot{m}$	=	Mass flow	[kg/s]
C_p	=	Molar specific heat of air	[J/kg · K]
T_{in}	=	Inlet air temperature	[K]
p_{out}	=	Discharge air pressure	[kPa]
p_{in}	=	Atmospheric air pressure	[kPa]
k	=	Specific heat ratio of air	[-]
P	=	Electrical compressor power	[kW]

It is of interest to note that Equation 2-2 is produced by rearranging Equation 2-1 so that the electrical compressor power is the subject of the formula.

Equation 2-2: Compressor power

$$P = \frac{\dot{m} C_p T_{in} \left(\left(\frac{p_{out}}{p_{in}} \right)^{\frac{k-1}{k}} - 1 \right)}{\eta_{comp}}$$

P = Electrical compressor power [kW]

$\dot{m}$ = Mass flow [kg/s]

C_p = Molar specific heat of air [J/kg · K]

T_{in} = Inlet air temperature [K]

p_{out} = Discharge air pressure [kPa]

p_{in} = Atmospheric air pressure [kPa]

k = Specific heat ratio of air [–]

η_{comp} = Compressor efficiency [–]

This shows that power is a function of the compressor efficiency, discharge pressure, and discharge flow of the compressor. Thus, aligning with the focus of the study, namely to control and reduce these principle pressure and flow parameters. This is done with the goal of producing energy savings with the resulting reduced power consumption.

Consumers

The distribution of the demands determines how the supply is used to meet the demand. The operational requirements (such as pressures and flows) of the demands determine the critical control parameters for the system. Knowing the individual demand requirements and locations are therefore all the more critical for developing an energy management strategy. Collecting information such as the demand locations, type (i.e. shafts or processing plants), pressure requirements, flow demand ranges, and which demands are controlled by valves is key [52].

2.2.1.2 Compressed air system operational schedules

With varying operational requirements [41] throughout a day period due to different equipment and activities, it is important to know the operational schedule of the mine. The different periods in the schedule determine the activities, the activities determine the equipment used, and the equipment determines the operational requirements. The requirements are further discussed in Section 2.3.4.2, but as they are dependent on the schedule, they must first be understood. There are three primary shifts in a typical mining schedule, namely the drilling shift, blasting shift, and cleaning shift.

Drilling shift

The drilling shift [52] is the peak demand period during which holes are drilled into the rockface with rock drills. Other equipment used during this shift is as indicated in Section 1.2.4 and is used to evaluate the operational requirements for the shift.

Blasting shift

The blasting shift [41] is the minimum demand period. After the drilling shift explosives are placed in the holes drilled in the rockface, the explosives are charged, and the areas evacuated. The explosives are detonated to break apart the rock containing the ore. The equipment used during this shift is as indicated in Section 1.2.4 and is used to evaluate the operational requirements for the shift.

Cleaning shift

The cleaning shift [41] is the intermediate demand period when the ore released during the blasting shift is loaded and pulled to surface. The demand during this period is less than during the drilling shift but greater than during the blasting period due to the use of the rock-moving equipment. The specific equipment used during this shift is as indicated in Section 1.2.4 and is used to evaluate the operational requirements for the shift.

The typical shaft demand flow profile and schedule for a platinum group mine are shown in Figure 2-2. The x-axis intersects the y-axis at zero to provide an indication of how the flow varies relatively throughout the different shifts.

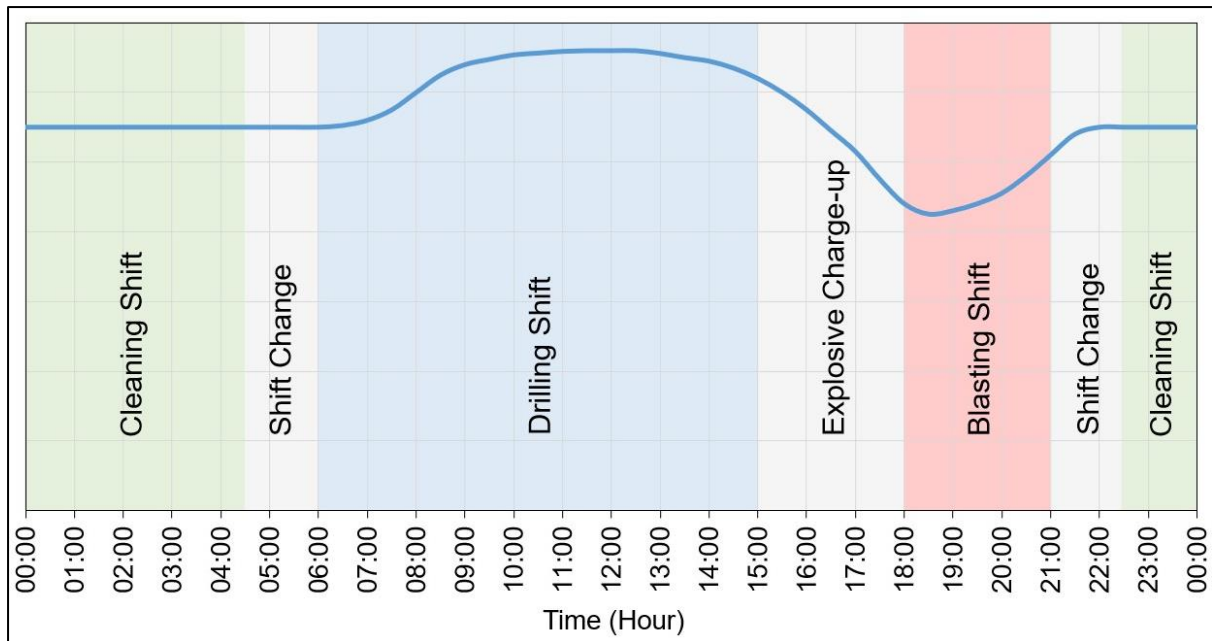


Figure 2-2: Typical platinum group mine demand flow profile and schedule (adapted from [41])

The typical shaft demand flow profile and schedule for a gold mine are shown in Figure 2-3.

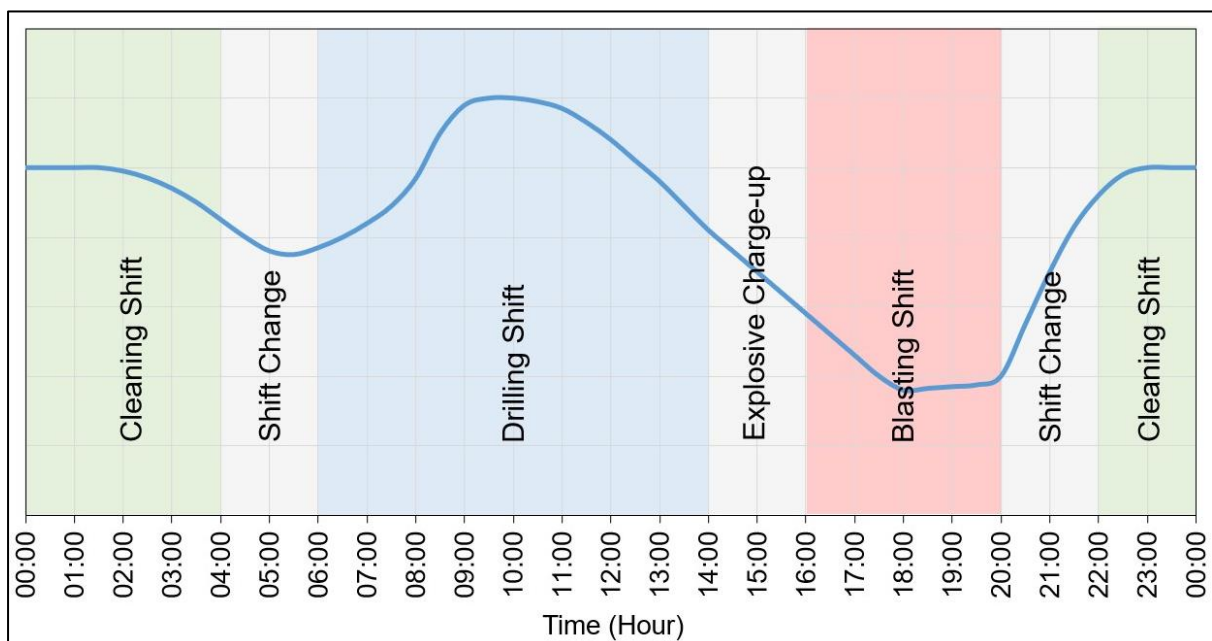


Figure 2-3: Typical gold mineshaft demand flow profile and schedule (adapted from [52])

The schedules in the two figures above are similar, and most mining activities in South Africa can be expected to have schedules of this sort. The reason is predominantly that mines align most work with common work hours. Furthermore, it may be in part due to the varying daily electricity tariffs charged by Eskom and mines aligning their lower demand periods with peak tariff periods. This puts less strain on the electrical grid and reduces operating costs. However,

all sites are unique and the operating schedule for the mine has to be obtained from the specific mine.

2.2.2 Determine infrastructure limitations

As this study focuses heavily on developing solutions around existing infrastructure, the infrastructure limitations must be identified from the start. This ensures that a strategy can be developed and implemented without delays or further capital investment. However, before the limitations can be investigated, the infrastructure to be considered must be identified first.

2.2.2.1 Infrastructure requirements

For the strategies investigated in the studies discussed in Section 1.3 it was observed and recorded in the respective tables that the following infrastructure requirements were either identified for the respective solutions or became apparent during implementation. These are the common requirements across the respective studies. As each mine is unique, there is the possibility that additional items will be required. The infrastructure requirements for the identified strategies are summarised in Table 2-1.

Table 2-1: Strategies infrastructure requirements

Strategies	Infrastructure
Valve control	• Compressed air pipelines • Control valves • Valve position sensors • Flow meters • Pressure transducers • Electric power meters • Valve PLCs • Communication networks • Historian/database • SCADA • Centralised control room
Guide vane control	• All the above,** and ○ Compressed air pipelines ○ Trimming compressors ○ Compressor subsystems ○ Inlet guide vanes ○ Guide vanes position sensors ○ Blow-off valves

Strategies	Infrastructure
	○ Blow-off valve position sensors ○ Flow meters ○ Pressure transducers ○ Electric power meters ○ Subsystem sensors ○ Compressor controllers ○ Subsystem controllers* ○ Guide vanes PLCs ○ Communication networks ○ Historian/database ○ SCADA ○ Centralised control room
Compressor schedules	• All the above;** and ○ Compressed air pipelines ○ Trimming compressors ○ Compressor subsystems ○ Blow-off valves ○ Blow-off valve position sensors ○ Flow meters ○ Pressure transducers ○ Electric power meters ○ Subsystem sensors ○ Compressor controllers ○ Subsystem controllers* ○ Communication networks ○ Historian/database ○ SCADA ○ Centralised control room ○ External simulation software* ○ Control panel system* ○ Monitoring system**
Automation of compressed air control	• All the above; and ○ Control panel system

(*) – Dependent on the system and only necessary when applicable; (**) – Optional and recommended but not a strict requirement

As the required infrastructure has been identified, the limitations can be investigated.

2.2.2.2 *Supply-side infrastructure*

Inspecting the infrastructure on the supply-side consists of looking at all systems surrounding the compressors and compressor houses. Some of the studies [35], [41], [51], [52] discussed in Section 1.3 were found to contain a combination of structured and fragmented details of inspections and/or investigations carried out on the required infrastructure for the respective strategies employed. Many of these assessments took place pre-emptively while others were overlooked and arose from necessity during implementation. In an effort to avoid encountering the same difficulties, this section summarises the critical supply-side infrastructure assessment points observed.

Compressors

Naturally, starting with the compressors themselves, the following additional information should be gathered about each compressor identified in Section 2.2.1.1:

- Is the compressor still available?
- Do the subsystems in the compressor and the compressor itself still function?
- Is the compressor and its subsystems calibrated?
- Are there special requests or limitations regarding the operation of the compressor?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Blow-off valves

Blow-off is not only an integral part of elaborate compressor control but of common operations such as stop/start sequences as well. The following information should be gathered about the blow-off of each compressor:

- Is the blow-off valve system still available?
- Do the subsystems of the blow-off system still function?
- Is the blow-off system and its subsystems calibrated fully?
- Are there special requests or limitations regarding the operation of the blow-off?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Guide vanes

Guide vanes are not only an integral part of elaborate compressor control but are also often stationary units calibrated to allow a compressor to operate efficiently. The following information should be gathered about the guide vanes of each compressor:

- Are the guide vanes available?
- Are the guide vanes actuated and, if so, is the system available and complete?
- Do the subsystems of the actuated guide vane system still function?
- Is the guide vane system and its subsystems calibrated fully?
- Are there special requests or limitations regarding the operation of the guide vanes?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Instrumentation

Instrumentation such as pressure transducers or flow meters are not only used for compressor control purposes but also foremost for monitoring systems. Considering the required infrastructure, the following information should be gathered about the instrumentation of each compressor to provide the required data:

- Is the instrumentation available?
- Is the instrumentation fully calibrated?
- Are there special requests or limitations regarding the use of the instrumentation?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Controllers

The various controllers are not only used for elaborate compressor control purposes but are also frequently used for common operations such as stop/start sequences, surge protection, and subsystem operations such as cooling or lubrication. The following information should be gathered about the controllers of each compressor:

- Is the compressor subsystem controller available?
- Is the primary compressor controller available?
- If guide vane control is being considered, is the guide vane PLC available?
- Are the controllers fully calibrated and operational?

- Are there special requests or limitations regarding the use of the controllers?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Communication network

The local communication network is not only used for compressor control purposes but also to communicate the data from the instrumentation to monitor systems. Many studies often overlook the communication network as it is assumed to fall under another system such as instrumentation during the design process. This occasionally results in difficulties with the reliability and availability of data and control later on. To avoid this, the following information should be gathered about the local communication network of each compressor to provide the required data:

- Is all the required network available?
- Is the network fully functional?
- Are there special requests or limitations regarding the use of the network?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

2.2.2.3 Demand-side infrastructure

Inspecting the infrastructure on the demand-side consists of reviewing all systems surrounding the compressed air from outside the compressor houses. This boundary is defined due to pipelines being consumers alongside the shafts, processing plants, and other operations. Again, in an effort to avoid encountering the same difficulties seen in the studies [35], [41], [51], [52] discussed in Section 1.3, this section summarises the critical demand-side infrastructure assessment points observed.

Pipelines

The compressed air pipe network is vital to pneumatic operations as end users can be several kilometres away from compressor houses. While other demands consume compressed air flow and pressure to operate machinery, pipelines consume airflow through leaks and pressure via frictional losses. The following information should be gathered about the compressed air pipe network:

- Is all the required pipe network available?
- Are there significant leaks or other losses?
- Are all pipe sections to code and sized correctly?
- Is the pipe network fully functional?
- Are there special requests or limitations regarding the use of the pipe network?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Control valves

Control valves not only regulate the pressure delivered to a consumer to manage consumption but also ensure that overpressurisation of equipment and resulting damage do not occur. The following information should be gathered about each identified control valve:

- Is the control valve system still available?
- Is the valve pneumatically actuated and, if so, what is the minimum actuator pressure?
- Do the subsystems of the control valve system still function?
- Is the control valve system and its subsystems calibrated fully?
- Are there special requests or limitations regarding the operation of the control valve?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Instrumentation

As discussed on the supply-side, apart from being used for control purposes, instrumentation is first and foremost used for monitoring systems. Considering the required infrastructure, the following information should be gathered about demand-side instrumentation to provide the required data:

- Is the instrumentation available?
- Is the instrumentation calibrated fully?
- Are there special requests or limitations regarding the use of the instrumentation?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Controllers

In comparison to the various controllers used on compressors, those used on valves are relatively simple but crucial. The following information should be gathered regarding the controllers of each valve:

- Is the valve PLC available?
- Is the controller fully calibrated and operational?
- Are there special requests or limitations regarding the use of the controller?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

Communication network

Again, the local communication network is not only used for control purposes but also to communicate the data from the instrumentation for the monitoring of systems. As discussed under the supply-side, many studies neglect to investigate the communication network independently and later run into problems. To avoid this, the following information should be gathered about the local communication network of the demand-side to provide the required data:

- Is all the required network available?
- Is the network fully functional?
- Are there special requests or limitations regarding the use of the network?

This information will be used to populate a table containing the system limitations in order to identify possible control strategies.

2.2.3 Determine measurement data availability

2.2.3.1 Data requirements

For the strategies investigated in the studies of Section 1.3 it was observed and recorded in the respective tables that the following data requirements were either identified for the respective solutions or later became apparent during implementation. These are the common requirements across the respective studies. As each mine is unique, there is the possibility that additional information will be required. The data requirements for the identified strategies are summarised in Table 2-2.

Table 2-2: Strategies data requirements

Strategies	Data
Valve control	• Consumer pressure requirement • Consumer post-valve pressure • Consumer pre-valve pressure • Consumer valve position • Consumer flow • Compressor discharge flow • Compressor electric power
Guide vane control	• All the above,** and ○ Consumer pressure requirement ○ Consumer-side pressure ○ Consumer flow ○ Compressor inlet guide vane position ○ Compressor blow-off valve position ○ Compressor discharge pressure ○ After-cooler discharge pressure ○ Compressor discharge flow ○ Compressor running status ○ Compressor electric power ○ Compressor alarm status ○ Compressor trip status ○ Compressor start sequence status ○ Compressor stop sequence status
Compressor schedules	• All the above,** and ○ Consumer pressure requirement ○ Consumer-side pressure ○ Consumer flow ○ Compressor discharge pressure ○ After-cooler discharge pressure ○ Compressor discharge flow ○ Compressor running status ○ Compressor loaded status ○ Compressor electric power ○ Compressor ready to start status ○ Compressor alarm status ○ Compressor trip status ○ Compressor start sequence status ○ Compressor stop sequence status

Strategies	Data
Automation of compressed air control	• All the above

(*) – Dependent on the system and only necessary when applicable; (**) – Optional and recommended but not a strict requirement

As the required data has been identified, the existence and accessibility of the data can be investigated.

2.2.3.2 Data management

Existence of data

Provided that the required infrastructure identified in Section 2.2.2 exists, the existence of the required data can now be investigated. Various sources of data exist on a mining site, being mining personnel, technical drawings, and/or databases [41]. In order to gain access to the required data, channels of communication must be established with the relevant personnel, be that instrumentation superintendents, technicians, or engineers [41].

In this case, the primary data source of interest is the mine database that stores data such as flow, pressure, power, and other process parameters. Furthermore, for analysis and control purposes, the data is required as both historical and real-time data and must thus be available directly from the SCADA or the historian.

Processing of data

Ensuring the data is processed properly is important to avoid confusion. The historian server software does this. When the incoming data is received, it is allocated a tag name, assigned a timestamp, and stored. A quick exercise of identifying the tag names of the relevant data, retrieving that data, and observing the trends give an initial overview of the data and how it compares against expectations.

Data quality and integrity

Some strategies such as those utilising simulation may be very sensitive to data irregularities. These strategies often use inputs from multiple data tags. Should one of these data sources malfunction, the controller would cease to function properly [35]. The quality and integrity of data can be determined by putting the data through a set of checks (adapted from [41]):

- Is the data complete?
 - Is the data free of gaps or blank entries?

- Is the data accurate?
 - Is the data free of outliers?
 - Does the data correlate with that of other measuring devices?
- Is the data consistent?
 - Is the data within the expected range?
- Is the data in context?
 - Do related parameters follow similar trends?

Should any data not pass all the checks, the erroneous data must be corrected where possible. Consistent issues should be adjusted for, and where data is unusable, estimations are required based on historical data or related parameters where possible.

2.2.4 Determine control and monitoring limitations

2.2.4.1 Software

The available software determines the level of automation possible for an individual mining site. By investigating what software is installed and available in the central controller (from Figure 1-8), the limitations of the system are identified. The first investigation simply ascertains whether the central controller has the following software as identified from literature:

- Is a historian in use?
 - What are the historian data extraction capabilities?
 - Are there policies or restrictions regarding access?
 - Are there policies or restrictions regarding programming and changes?
- Is a SCADA in use?
 - What are the active SCADA control capabilities?
 - Are there policies or restrictions regarding access?
 - Are there policies or restrictions regarding programming and changes?
- Is a monitoring system installed?
 - What are the active monitoring capabilities?
 - Are there policies or restrictions regarding access?
 - Are there policies or restrictions regarding programming and changes?
- Is a control panel system installed?
 - What are the active control capabilities?
 - Are there policies or restrictions regarding access?
 - Are there policies or restrictions regarding programming and changes?

2.2.4.2 Data accessibility

In order to carry out investigations and control, easy access to the required data is imperative. If a historian is available, this should not be a problem [35]. However, the data access interface and its capabilities influence the ability to establish quick and easy tools for the implementation of projects without having to interfere with the software and internal SCADA and communication network data streams.

2.3 Evaluate operational requirements

2.3.1 Determine principle strategies and requirements

For this study, identifying the principles behind popular automated control strategies is of little value without determining the alternative strategies and requirements to achieve the same goals. This section investigates the individual strategies and the respective principles to identify compatible alternative strategies and the respective requirements for implementation. Compatible alternative strategies can be determined for one strategy by identifying matching principles between this strategy and others.

2.3.1.1 Manual network control principles

The strategies considered in Section 1.3 are all automated control strategies and are thus reliant on more advanced control systems. These systems are not always in place; therefore, to ensure that principle-based implementation of these automated control strategies is possible on manually controlled compressed air systems, a manual strategy that shares common principles must also be considered.

The strategy under consideration is manual network control as discussed in Section 1.2.5 since it is one of the simplest and most common manual control strategies used on mine compressed air networks. This strategy is fundamentally the same as compressor schedules apart from it lacking simulation software or a control panel system.

Just as compressor schedules have the primary control principles of efficiency, flow, and pressure, so does manual network control. The controlled regions are efficiency and flow at the compressors and all pressures downstream of the compressors. The primary system difference when compared with compressor schedule control is the use of an operator instead of simulation software or a control panel system.

As with compressor schedule control, there are a variety of different approaches to manual network control. The most common provides the operator with pressure targets that satisfy

the demand-side pressure requirements on the ring. From their own experience, operators must start and stop compressors to keep to these pressure targets. Some more experienced operators may evaluate the distribution of demand flows and pressures of the system and select compressors that will be able to match that distribution, and supply the air needed to meet those demands. In some cases, compressor conditions or efficiencies may influence the order in which the operator prioritises the compressors. The operator continuously monitors the system to follow the changing demands.

Due to a lack of recent studies that have implemented manual network control, it is assumed that the strategy requirements are very similar to those of compressor schedule control. The requirements were determined by simply excluding the simulation software and control panel system from that of compressor schedules. The data and infrastructure requirements for this strategy are summarised in Table 2-3.

Table 2-3: Manual network control implementation requirements

Infrastructure	Data
• Compressed air pipelines • Trimming compressors • Compressor subsystems • Blow-off valves • Blow-off valve position sensors • Flow meters • Pressure transducers • Electric power meters • Subsystem sensors • Compressor controllers • Subsystem controllers* • Communication networks • Historian/database • SCADA • Centralised control room • Monitoring system**	• Consumer pressure requirement • Consumer-side pressure • Consumer flow • Compressor discharge pressure • After-cooler discharge pressure • Compressor discharge flow • Compressor running status • Compressor electric power • Compressor ready to start status • Compressor alarm status • Compressor trip status • Compressor start sequence status • Compressor stop sequence status

(*) – Dependent on the system and only necessary when applicable; (**) – Optional and recommended but not a strict requirement

These requirements will serve to identify whether the strategy can be implemented on a system without later encountering data or infrastructure limitations.

2.3.1.2 Valve control

Pressure control is the principle behind valve control for compressed air downstream of the valve only. As all of the other identified strategies are located upstream of the valves and share the same pressure control principle, they are all compatible alternative strategies provided that the respective requirements are met. According to the location and control principles behind valve control, the four alternative strategies are:

- Manual network control (MNC);
- Guide vane control (GVC);
- Compressor schedules (CS); and
- Automated compressor control (ACC).

Abbreviations are provided for use later in this study. The requirements for these strategies were identified in Section 1.3 and will be used to complete the required checks later on.

2.3.1.3 Guide vane control

Guide vane control has two alternative strategies that share the pressure control principle and cover the same control region. Either strategy can be used provided that the respective requirements are met. The two guide vane control principle strategies are manual network control and compressor schedules. The requirements for these strategies have already been identified in Section 1.3 and will be used to complete the required checks later on.

2.3.1.4 Compressor schedules

Compressor schedule control has only one compatible alternative strategy provided that the requirements are met, namely manual network control. The requirements for this strategy were already identified in Section 1.3 and will be used to complete the required checks later on.

2.3.1.5 Automation of compressed air control

Both automated compressed air control and automated compressor control unfortunately do not have any alternative strategies. They are both completely reliant on their respective primary control systems. The first two primary control systems are guide vane control and compressor schedules, while the addition of valve control is considered in the case of automated compressed air control. A control panel system is required to implement the automated control, as it allows for communication and dynamic control of the primary control systems.

Automated compressed air or compressor control can, therefore, only be implemented fully and not undergo principle-based implementation. Furthermore, automated compressor control is a viable alternative strategy for principle-based implementation of valve control only. However, automated compressed air control is not a viable alternative option for any of the other strategies due to its dependency on those strategies. The automated control strategies will remain in this study but only as part of the strategies that can be implemented fully.

2.3.2 Compile elimination rubric

In order to identify strategies that can either be implemented fully or undergo principle-based implementation, an elimination rubric must be developed. The rubric is completed based on the information gathered regarding the completeness of the system infrastructure and data.

2.3.2.1 Full implementation

First it is important to identify which strategies can be fully implemented immediately. The strategy that follows the last fully implemented strategy will be considered for principle-based implementation.

The infrastructure and data requirements of the strategies are shown in Table 2-1 and Table 2-2, respectively. In order to evaluate a system, the available infrastructure and data of the system have to be investigated and the requirements met. Once the investigation has been completed, the checks can be completed in the rubric shown in Table 2-4.

Table 2-4: Strategies full implementation checks

Strategies	Infrastructure	Data	Completeness
Valve control	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete
Guide vane control	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete
Compressor schedules	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete
Automation of compressed air control	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete

Both infrastructure and data requirements would have to be found to be complete to constitute completeness. Once this rubric has been completed, the relevant principle-based implementation rubric can be completed.

2.3.2.2 Principle-based implementation

As the strategies that can be implemented fully have been identified, the strategies with the potential to undergo principle-based implementation must now be investigated. In order to evaluate a system, the available infrastructure and data of the system have to be investigated and the requirements met for each set of strategies.

The checks to be done for principle-based implementation of the individual strategies are shown in Table 2-5.

Table 2-5: Strategies principle-based implementation checks

Strategies	Infrastructure	Data	Implementation
Valve control	☐ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete	☐ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete	☐ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete
Guide vane control	☐ MNC complete ☐ CS complete ☐ All incomplete	☐ MNC complete ☐ CS complete ☐ All incomplete	☐ MNC complete ☐ CS complete ☐ All incomplete
Compressor schedules	☐ MNC complete ☐ All incomplete	☐ MNC complete ☐ All incomplete	☐ MNC complete ☐ All incomplete

Both infrastructure and data requirements would have to be found to be complete to constitute completeness for implementation of a strategy. Once all the checks have been completed, the elimination rubric can be completed.

2.3.3 Determine implementation strategies by elimination

Use the checks done in the previous section to eliminate strategies in the elimination rubric shown in Table 2-6.

Table 2-6: Strategies elimination rubric

Strategies	Full	Principle	Implementation
Valve control	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete ☐ N/A	☐ Full ☐ Principle ☐ None
Guide vane control	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete ☐ N/A	☐ Full ☐ Principle ☐ None
Compressor schedules	☐ Complete ☐ Incomplete	☐ Complete ☐ Incomplete ☐ N/A	☐ Full ☐ Principle ☐ None
Automation of compressed air control	☐ Complete ☐ Incomplete	N/A	☐ Full ☐ None

Full implementation would naturally be preferred where possible and would be selected over principle-based implementation. Once the elimination rubric has been completed, the way forward should be clear.

For example, should the requirements for full implementation of valve control be complete, full implementation would be selected as the way forward regardless of the state of the principle requirements. Additionally, should principle-based implementation and not full implementation of guide vane control be possible, this would be an addition to the way forward. With no other forms of implementation of other strategies possible, the elimination process would be complete and the way forward clear. The way forward in this case would be both full implementation of valve control and principle-based implementation of guide vane control.

2.3.4 Obtain principle targets

This section discusses how to determine the control targets according to the strategies determined. Firstly, targets based on historical data are needed to provide the starting targets for control. Secondly, end user targets are needed to provide the final ideal targets toward which to iterate. An iterative approach is used to improve control and avoid causing harm to systems that may not have been identified as problematic beforehand (for example, sensitive and underperforming fridge plants that may need higher compressed air pressures than expected due to inefficiencies).

2.3.4.1 Historical data analysis

Once the strategy has been identified, gather the required data as identified in the relevant tables. There may be multiple types of data required, but there is one common requirement between all the strategies and that is the consumer pressure requirement.

Do a historical data investigation of the trends to identify their common operational pressures, eliminating outliers. A common method is to use average full-day profiles or frequency plots for specific periods or shifts in the day. A similar method was used by Jonker [52] to identify targets in their study. This can be used as an initial guide for expectations or a starting point for gradual reductions.

2.3.4.2 End user requirements

Once the demands have been identified and the operational schedules (from Section 2.2.1.1) and any limitations that would affect them are known, the expected end users can be identified and allocated to their periods in the schedule. Should advanced control be planned where flow is a control factor, each demand has to be investigated further to get working crew sizes and schedules in order to determine the total demand required.

The end user requirements are determined from the common requirements discussed in Section 1.2.4. The requirements are used for the ideal targets. These targets must first be adjusted if needed and signed off by each demand-side engineer to ensure the actual requirements are met. Similar methods were used by De Jager [41], Bredenkamp [43], and Jonker [52] to identify system control targets in their studies.

For example, considering the average pressure requirements and the active periods of all of the demand-side operations from Section 1.2.4, the maximum pressure requirements for the three primary shifts are:

- Drilling: 510 kPa.
- Blasting: 475 kPa (or 250 kPa – agitators and other instrumentation rarely used during the shift).
- Cleaning: 500 kPa.

These pressures may be used as a guide to set up the ideal target pressures. However, consulting the shaft or demand-side engineer is imperative to ensure the proper target pressures are approved as the applicable demand-side operations and requirements may differ.

2.4 Develop implementation strategy

2.4.1 Identify and implement control

2.4.1.1 Required control

Once the primary strategy and the principle targets have been determined in Sections 2.3.3 and 2.3.4, the possible control options to implement the strategy and achieve the targets can be identified. Using the known infrastructure and control available from Section 2.2, identify which of the control approaches for the strategy determined would be applicable should the strategy have more than one option. For example, compressor schedules have multiple control options depending on the available data and infrastructure. In this case, should compressor efficiencies not be available, the compressor schedules would simply control based on pressure and flow alone.

2.4.1.2 Control implementation

Once the required control is known from the previous section, determine how this control will be implemented. The available software determines the level of automation possible. However, whether changes to the system would be allowed is primarily dependent on the specific mine's information technology (IT) policies [35].

Using the known software as gathered in Section 2.2.4, the level of automation possible and approach to implementation are investigated. Should the required software exist and changes be allowed or even possible, further automation can be investigated. Conversely, should it not be possible to automate the control further but control room operators are available, a manual approach to the control can be investigated. It is important to note that training of mining personnel is required in both cases.

2.4.2 Identify and implement monitoring approach

2.4.2.1 Required monitoring

Once the control implementation approach has been determined, the parameters to be monitored can be identified. The parameters required may differ depending on the individual carrying out the specific monitoring duties. For example, a control room operator only needs to see the control parameters while an energy manager needs to see the control parameters as well as the system energy consumption or savings.

Looking at the important information needed for the specific strategy and/or control as discussed in Section 2.4.1, the control parameters to be monitored can be identified. Should further parameters be required for other individuals or purposes, they can be added accordingly.

2.4.2.2 Monitoring implementation

Since the required parameters and monitoring have been established in the previous section, how monitoring will be implemented can be determined. Much like the control implementation, this is heavily reliant on the available software and IT policies of the specific mine.

Considering the data and software availability identified in Sections 2.2.3 and 2.2.4, the possible monitoring methods can be identified. Should the required data and software exist and changes be possible, automation of the monitoring process can be investigated further. Conversely, should it not be possible but there is acceptable access to the necessary data, a more manual approach can be investigated. For example, both studies by Van Heerden [35], [51] experienced limitations with data reliability and client policies that hindered the automation of the control. The developed control produced outputs that were used in an advisory capacity to guide the operators' control decisions through a monitoring system.

Although specialised monitoring software is ideal, simpler solutions that are less time-consuming and costly to implement are also often possible. Some examples include using the special features on the available SCADA or custom dashboards built in commonly available software or programs such as Microsoft Excel or Microsoft Power BI.

Further monitoring for management purposes is of utmost importance to primarily ensure the control is being implemented correctly, targets reached, and savings obtained. The success of the savings project depends on continuous monitoring of the project implementation and performance.

2.5 Verify and validate solution

Showing the value of a solution and its ability to reliably meet expectation is key to motivating its implementation from the start. This is not only critical at the beginning of any project, but also during the continuous monitoring and final evaluation of the success of a project and the implemented solution. Additionally, should more than one possible strategy be identified, the theoretical values are used to identify and select the most effective solution.

2.5.1 Develop baselines and theoretical values

This section provides guidance for baseline development and details the process of calculating the theoretical energy improvement projections used to verify the solution.

2.5.1.1 Baseline development guidelines

The purpose of baselines is to keep reference points for the relevant system characteristics such as pressure, flow, and power. These baselines are developed from data recorded prior to the implementation of the proposed solution. There are two primary uses for these baselines:

- Developing projections of the theoretical or expected energy improvements for the proposed solution.
- Evaluating the impact of the implemented solution so that it may be verified.

As all compressed air networks are unique, it is important to consult the IPMVP that indicates key points for accurate baseline development [58]. From the IPMVP, the three most important topics are:

- Measurement boundary
 - Define the system boundary where the solution will be measured and verified against a baseline.
- Measurement period
 - Determine whether adjustments are required to account for seasonal effects on the system.
 - Identify recent system changes that require adjustments to mitigate any effect on the baseline accuracy when representing the current system.
 - Investigate whether multiple baselines are required to represent individual modes or scheduled periods of operation during which the activities of each period differ.

- Adjustment methods
 - Perform non-routine baseline adjustments when a system change occurs after the baseline period and that severely affects the baseline accuracy.
 - Use routine baseline adjustments when baseline scaling is required to account for an external variable that influences the baseline.

For this study it is assumed that the necessary pressure, flow, and power meters are operational and available on the system surface, and this forms the measurement boundary. The remaining points previously listed are either addressed in the following sections or investigated independently for each compressed air network considered. The specific methods used to develop baselines from historical data are discussed in Section 2.3.4.1.

2.5.1.2 Theoretical energy improvement calculation method

In order to determine the theoretical energy improvement, the impact of the controlled parameter must be determined. As most of the strategies highlighted in this study focus on pressure control, this section shows the process of determining the impact of said pressure control. Should a more advanced strategy be used where flow control is active, this same process can be followed simply by skipping over the first part concerning pressure.

For pressure control, the theoretical pressures or pressure targets are determined as described in Section 2.3.4. These targets as well as the pressure, flow, specific power, and KPI baselines are also required to calculate the projected and theoretical values going forward.

Resistance to pressurised flow

The resistance to pressurised flow is the resistance a demand exhibits against its nominal flow rate per unit pressure. The nominal flow, also referred to as the normalised flow, is calculated by normalising the measured flow to a constant pressure and temperature, namely standard atmospheric conditions. The resistance to pressurised flow is also known as the demand KPI, and from this point onward will be referred to as such for the remainder of this study. The demand KPI for each consumer is determined individually and summed together to produce the system demand KPI. Equation 2-3 is derived from the ideal gas law and represents the relationship between two instances of a steady-state system KPI value. This derivation is explained in more detail in Appendix C.

Equation 2-3: Ideal gas law derivation of resistance to pressurised flow (adapted from [56])

$$\frac{\dot{Q}_1}{p_1} = \frac{\dot{Q}_2}{p_2}$$

$$\dot{Q}_1 = \text{Nominal flow at time 1} \quad [Nm^3/h]$$

$$p_1 = \text{Supply pressure at time 1} \quad [kPa]$$

$$\dot{Q}_2 = \text{Nominal flow at time 2} \quad [Nm^3/h]$$

$$p_2 = \text{Supply pressure at time 2} \quad [kPa]$$

By defining the left and right sides of Equation 2-3 as the projected and baseline demand KPI values, respectively, suggests that the baseline and projected values are equal. However, this is only true when no changes to the system occur between the baseline and projected periods. In most real-world scenarios, this is not the case as the demand KPI is transient and either increases due to expanding activities and wastage growth or decreases due to closing of working areas. Demand KPI values thus rarely remain constant and the projected demand KPI must be determined by a projection of the baseline trend. This results in the projected demand KPI being adjusted by a constant percentage for each influential change as shown in Equation 2-4.

Equation 2-4: Projected resistance to pressurised flow

$$KPI_P = (1 + c_1 + c_2 + \dots + c_i) \times KPI_B$$

$$KPI_P = \text{Projected resistance to pressurised flow} \quad [Nm^3/kPa \cdot h]$$

$$c_i = \text{Constant percentage adjustment} \quad -$$

$$KPI_B = \text{Baseline resistance to pressurised flow} \quad [Nm^3/kPa \cdot h]$$

Utilising the demand KPI baseline and Equation 2-4, the projected demand KPI can be determined. Equation 2-3 is used to derive Equation 2-5.

Equation 2-5: Pressurised flow

$\dot{Q} = p \times KPI$		
$\dot{Q}$	=	<i>Nominal flow</i> $[Nm^3/h]$
p	=	<i>Supply pressure</i> $[kPa]$
KPI	=	<i>Resistance to pressurised flow</i> $[Nm^3/kPa \cdot h]$

Equation 2-5 will be used to determine the system demand theoretical and projected flows.

Flow

Should the selected strategy use pressure control, the future theoretical flow is calculated using Equation 2-5, the projected KPI, and theoretical pressures. The resulting profile indicates the expected flows for the system after the solution is implemented. However, should a strategy be used where flow control is utilised, the theoretical flow would come from the developed targets as described in Section 2.3.4.

In either case, the future projected flow is calculated with Equation 2-5, projected KPI, and baseline pressures. The resulting profile represents the would-have-been flow of the system should no control have been implemented.

Specific power

The specific power of a supplier in the context of this study is the energy density of the compressed air it produces, calculated as the power per unit nominal flow rate as shown in Equation 2-6.

Equation 2-6: Specific power (adapted from [45])

$$SP = \frac{P}{\dot{Q}}$$

SP	=	<i>Specific power</i>	$[kW \cdot h/Nm^3]$
P	=	<i>Power</i>	$[kW]$
$\dot{Q}$	=	<i>Nominal flow</i>	$[Nm^3/h]$

The specific power values for the individual suppliers on the system are calculated first and the average of these values is considered the system specific power. The system specific power baseline is determined first, whereafter the theoretical system specific power is investigated.

Equation 2-2 shows that compressor power is directly proportional to the pressure it supplies. Therefore, the theoretical supply-side pressure resulting from the selected control strategy must be known to determine the theoretical system specific power. While the more common pressure control strategies would provide this in Section 2.3.4, a flow control strategy would have to rearrange Equation 2-5 to provide the expected or theoretical supply-side pressures.

In order to calculate the theoretical system specific power values, Equation 2-7 was derived from Equation 2-2. This derivation is shown in Appendix C.

Equation 2-7: Theoretical specific power

$$SP_T = SP_B \times \left(\frac{p_T^{\frac{k-1}{k}} \times p_{in}^{\frac{1-k}{k}} - 1}{p_B^{\frac{k-1}{k}} \times p_{in}^{\frac{1-k}{k}} - 1} \right)$$

SP_T	=	<i>Theoretical specific power</i>	$[kW \cdot h/Nm^3]$
SP_B	=	<i>Baseline specific power</i>	$[kW \cdot h/Nm^3]$
p_T	=	<i>Theoretical supply pressure</i>	$[kPa]$
k	=	<i>Constant (1.4)</i>	—
p_{in}	=	<i>Inlet/atmospheric pressure</i>	$[kPa]$
p_B	=	<i>Baseline supply pressure</i>	$[kPa]$

Using Equation 2-7 and assuming the inlet/atmospheric pressure is under standard conditions, the theoretical specific power values can be calculated. The theoretical system specific power is used to calculate the theoretical and projected power values.

Power

The method used to evaluate the total theoretical power remains the same when considering supply- and demand-side strategies individually or combined. Additional steps are only required when a combination of supply- and demand-side strategies is used and the impact of each strategy needs to be determined. Regardless of the specific arrangement, the various system power values are calculated by multiplying the nominal flow by the system specific power as shown in Equation 2-8, derived from Equation 2-6.

Equation 2-8: System power

$P = \dot{Q} \times SP$			
P	=	Power	[kW]
$\dot{Q}$	=	Nominal flow	[Nm ³ /h]
SP	=	Specific power	[kW · h/Nm ³]

The 2019 theoretical power is calculated using Equation 2-8, the theoretical flow, and theoretical specific power. The resulting profile represents the expected power profile for the system after the solution is implemented. As mentioned, this is the theoretical power for all arrangements, and only the projected power varies with the different cases.

The total 2019 projected power is calculated with Equation 2-8, the projected flow, and baseline specific power. The calculated profile represents the would-have-been power of the system should no control have been implemented.

These two profiles alone are sufficient for most arrangements, and the difference between them is the total theoretical power improvement. This is used to calculate the total theoretical daily energy impact using Equation 2-10 that is then used to calculate the total theoretical daily cost savings. Both the energy and cost values are extrapolated to determine the annual total theoretical energy and cost savings to be expected.

In the case where a combination of supply- and demand-side strategies is implemented and the individual impacts are required, the supply-side impact is calculated next. The supply-side theoretical power is the same as the total theoretical power. The supply-side projected power is determined using Equation 2-8, the projected flow, and theoretical specific power.

The produced profile represents the would-have-been power of the supply-side system should no control have been implemented to manage the supply. The difference between this profile and the total theoretical power is the supply-side theoretical power improvement portion of the total theoretical power improvement.

The demand-side theoretical power improvement is calculated in one of two ways. The first and simplest approach is subtracting the supply-side theoretical power improvement from the

total system theoretical power improvement. The second method is to first calculate the demand-side projected power with Equation 2-8, the theoretical flow, and baseline specific power.

This profile represents the would-have-been power of the demand-side system should no control have been implemented to manage the demand. The demand-side theoretical power improvement is calculated by taking the difference between the demand-side projected power profile and the total theoretical power.

If needed, the percentage of the total theoretical power improvement that the supply- and demand-side portions each hold can be calculated. As the supply- and demand-side portions of the actual power and energy improvements cannot be calculated without complex and lengthy calculations, the theoretical percentages can be used to estimate the actual values.

2.5.2 Calculate energy improvement

The actual energy improvement must be calculated to show and acknowledge the value of the developed solution. This will later be used to verify the solution accuracy as well as validate the solution under the study objectives and problem statement. This section shows the method used to calculate the actual energy impact.

Section 2.5.1.1 highlighted several factors that may affect the baseline used to calculate the energy impact of the solution. Therefore, before the impact is calculated, the following points must be addressed first:

- Seasonal effects
 - Account for seasonal effects by developing baselines over a full-year period.
- Different modes or periods of operation
 - This study only focuses on standard weekday operating periods and does not include weekends, thus multiple baselines are not required.
- System changes
 - Should a significant and permanent system change occur after the baseline period, perform a non-routine baseline adjustment as described in Section 2.5.2.1.
- External influential variables
 - Compressed air consumption is influenced by the intensity of production-related activities and routine baseline adjustments must be performed to account for this as described in Section 2.5.2.2.

2.5.2.1 Non-routine baseline adjustments

When a significant and permanent system change is encountered, the impact that change has on the baseline's ability to accurately represent a current would-have-been scenario must be quantified. Once the impact of the change is known, the baseline or actual profile must be adjusted to counteract the effects of the change. As a system change could take a multitude of forms, providing a single solution to resolve all possible changes becomes increasingly problematic. A logical process needs to be followed to resolve the problem caused by a particular change encountered on a case-by-case basis.

For example, should an additional compressor be installed on a compressed air network outside the scope and control of the relevant solution being implemented, this has to be accounted for. In this example, the sole purpose of the new compressor would be to increase and improve peak drilling shift pressures and, therefore, it would only operate during that period. As the pressure and power baselines were developed before this, the profiles would no longer be representative of the new system as there would be an elevated peak during the drilling shift with no change outside this period.

The use of a routine baseline adjustment would not counteract the effects of the change should the baseline undergo a routine baseline adjustment as described in Section 2.5.2.2. The flatter baseline profile would simply scale up to the peak of the actual profile. This would result in significant false savings being calculated outside the peak drilling period. Should the baseline not undergo a routine baseline adjustment, the resulting energy impact would show significant losses during the drilling shift where the actual peak values exceeded the baseline. In both cases, the savings or losses calculated would be unrelated to the implemented solution.

To counteract the effect of the change, the average operating power or electrical capacity of the additional compressor must be added to the baseline profile during the peak drilling period. This provides a more accurate representation of the would-have-been scenario.

2.5.2.2 Routine baseline adjustments

The intensity of production-related activities, specifically the number of active authorised end users during the drilling shift, has historically been directly proportional to the compressed air consumed during that period [59]. In order to account for fluctuations in the number of these active end users and thus production, a routine baseline adjustment must be performed.

As a result of the strong correlation found during the peak of the drilling shift, the baseline is scaled according to the average compressed air consumption during this period from 08:00 to

12:00. As compressor power consumption is directly proportional to the compressed air consumption, the compressor power baseline can be scaled directly. The scaled baseline is simply calculated using the same ratio between the respective pairs as shown in Equation 2-9.

Equation 2-9: Routine baseline adjustment

$P_{SB} = P_B \times \frac{P_{DAA}}{P_{DAB}}$			
P_{SB}	=	<i>Scaled power baseline</i>	[kW]
P_B	=	<i>Power baseline</i>	[kW]
P_{DAA}	=	<i>Drilling shift average actual power</i>	[kW]
P_{DAB}	=	<i>Drilling shift average baseline power</i>	[kW]

This scaled power baseline is used to calculate the actual energy improvement.

2.5.2.3 Actual energy improvement

Finally, the actual energy improvement can be calculated. This is done by first subtracting the actual power at each time interval over a 24-hour period from the corresponding scaled power baseline value. These values are then summed and multiplied by the measurement interval as shown in Equation 2-10.

Equation 2-10: Energy improvement

$$E = (P_{Ref} - P_{New}) \times \Delta t$$

E	=	Energy improvement/saving	[kWh]
P_{Ref}	=	Reference power profile (baseline/projected)	[kW]
P_{New}	=	New power profile (actual/theoretical)	[kW]
Δt	=	Measurement interval	[Hours]

This produces the energy improvement for that day. These daily values are extrapolated to give a prediction of the actual annual benefit should a yearlong implementation period not be possible. However, should a yearlong implementation period be used, the daily energy savings can simply be summed.

Additionally, while calculating the daily energy improvement, the energy saving for each measurement interval can be multiplied by the relevant Eskom tariff to produce daily and annual cost savings as well.

2.5.3 Verify solution

When the actual energy improvement has been calculated, the accuracy of the theoretical model can be verified by comparing the actual values with the relevant theoretical values. However, the accuracy of the theoretical values would be affected by:

- Significant system or operational changes that occur during implementation due to factors outside the control or scope of the solution.
 - Changes with long-term effects require a non-routine baseline adjustment.
 - The impact of the change must be filtered out for temporary changes where the affected period is sufficiently short.
- The initial target or theoretical control parameter, in this case pressure as determined in Section 2.3.4, not being implemented or met due to factors outside the control or scope of the solution.
 - The theoretical or target control parameter must be updated to that which was successfully implemented, and the theoretical energy improvement reevaluated.

In the event of any of these issues arising, the provided actions must be taken to produce an accurate theoretical model of the actual implemented solution. The percentage error of the updated theoretical model is calculated by using Equation 2-11 to compare the theoretical and actual energy improvement values. An error of less than 5.0% should be obtained in order to maintain the accuracy of the data. This is due to the majority of mining instrumentation operating with a measurement accuracy of 95%, which also aligns with the standard 95% confidence interval used for statistical analysis.

Equation 2-11: Percentage error of theoretical energy improvement

$$\%Error = \frac{|E_T - E_A|}{E_A}$$

$$\%Error \leq 5.0\%$$

E_T	=	<i>Theoretical energy improvement</i>	[GWh]
E_A	=	<i>Actual energy improvement</i>	[GWh]

The same process can be followed for the cost savings, which may provide more insight into the average distribution of implementation as the Eskom TOU tariffs vary throughout a day period.

2.6 Conclusion

The solution presented in Chapter 2 saw the development of a methodology for identifying, implementing, and evaluating control strategies possible within the capabilities of the existing limited infrastructure on a mine compressed air network.

First, the method for identifying control strategies for full or principle-based implementation was developed. This was followed by the development of the method for determining the theoretical energy improvement of a proposed control strategy. The purpose of the latter was primarily for motivating and evaluating the effectiveness of the provided solution. However, in rare cases where more than one strategy is identified with the first method, the method is used to evaluate and select the most effective of the possible solutions. Unlike most, these methods do not have to minimise lead times or capital costs as the criteria of this study specified that selected strategies had to function within the existing system limitations.

The solution started with a system analysis that provided a detailed approach to investigating the existing network layout, the locations and capacities of the available suppliers and consumers, and the operational schedules used. This was followed by creating a detailed breakdown of the limited infrastructure, data, systems, and software critical to the variety of common strategies.

The evaluation of operational requirements started by first introducing manual network control as an additional strategy to provide an alternative for systems severely devoid of infrastructure. Defining the implementation requirements for manual network control proved challenging due to the limited availability of literature. This was followed by identifying the various strategies and the respective counterparts to be used in the event of principle-based implementation thereof. The strategy identification method was developed and the process of determining the control parameter targets was laid out. This had multiple iterative steps, including evaluating demand-side operational requirements to ensure the most effective control targets were put forward.

The solution implementation strategy first focused on the control requirements and the available tools and systems to enable said control. The same was done concerning monitoring – identifying what was required and how to carry it out.

The verification and validation process started with baseline development, and guidelines in this regard were provided based on critical topics highlighted by the IPMVP. The evaluation method was developed, and some points raised in the baseline development guidelines were addressed and the techniques used to perform baseline adjustments introduced. How the actual energy improvement would be calculated was presented. The process used to verify the theoretical model and the solution accuracy was shown, which highlighted the importance of accounting for influential system changes.

CHAPTER 3: IMPLEMENTATION AND RESULTS

3.1 Preamble

This chapter discusses how two case study compressed air networks were used for the implementation of the methodology developed in Chapter 2. Systems A and B were used and form part of the same deep-level platinum mining group in the North West province of South Africa. System A is the largest of the two systems spanning 38 km between its furthest points, while System B is the smallest at 17 km.

For each case study, the process began with a system analysis to gain a detailed understanding of the existing compressed air network. The locations and capacities of each of the suppliers and consumers were recorded, and the relevant infrastructure and operational schedules studied. A detailed breakdown of the limited infrastructure, data, systems, and software considered critical was completed.

The chapter explains how the potential strategies and associated control parameters were identified and the target values calculated. This was done by analysing historical data, evaluating demand-side operational requirements, and consulting with demand-side engineers. Baseline development followed along with investigations to identify any need for baseline adjustments. The theoretical energy improvement values were determined with the developed method and later adjusted to account for any implementation restrictions.

The chapter discusses how the required control and monitoring were determined, and the implementation strategy thereof developed. Hereafter, the solution was implemented on the case study systems, followed by the calculation of the actual energy improvement. The actual energy improvement was compared with the predicted theoretical value, which provided verification of the theoretical model.

Finally, the chapter concludes with a critical discussion of the study results to highlight the important values and related observations. The study problem statement and objectives are discussed and the results validated. By extrapolating the savings obtained in this study across the South African mining industry, the potential benefit is determined.

3.2 Case study – System A

In 2019, the developed solution from Chapter 2 was implemented on a case study, System A. System A-1 denotes the configuration of System A shortly before the solution was first implemented early in 2019.

3.2.1 Implementation of solution

3.2.1.1 System analysis

At the beginning of 2019, the compressed air pipe network of System A-1 spanned 38 km. It connected seven compressor houses with a total of nineteen compressors to eight individual demands, namely one processing plant and seven active mineshafts. The compressed air system was analysed as discussed in Section 2.2.

Compressed air system layout

The compressed air network, suppliers, and consumers were first identified and are shown in the satellite imagery in Figure 3-1. The compressed air network was a ring-feed system that fed its demands from four VK50 and fifteen VK32 compressors as indicated in Figure 3-1 by the grey and black compressors, respectively. The number that follows the letters “VK” on the figure indicates the compressors’ ideal design capacities. Thus, although the VK50 and VK32 compressors have ideal design capacities of 5 MW and 3.2 MW, respectively, in reality, this is not the case. The average peak electric power capacity of each compressor was 4.8 MW and 2.9 MW for the VK50s and VK32s, respectively. Thus, giving the system a total peak electrical capacity of 62.7 MW. The average operating flow capacities of the compressors was 43 600 Nm³/h and 26 400 Nm³/h for the VK50s and VK32s, respectively. However, the capacities mentioned are the average operational capacities that differ slightly between individual compressors. These capacities fluctuate with pressure, and the installed capacities are slightly higher due to further inefficiencies.

Although guide vanes were already installed on the compressors, none were controlled actively. The use of compressor schedules was also non-existent. Compressors were started and stopped manually to maintain pressures far above what were required by the consumers.

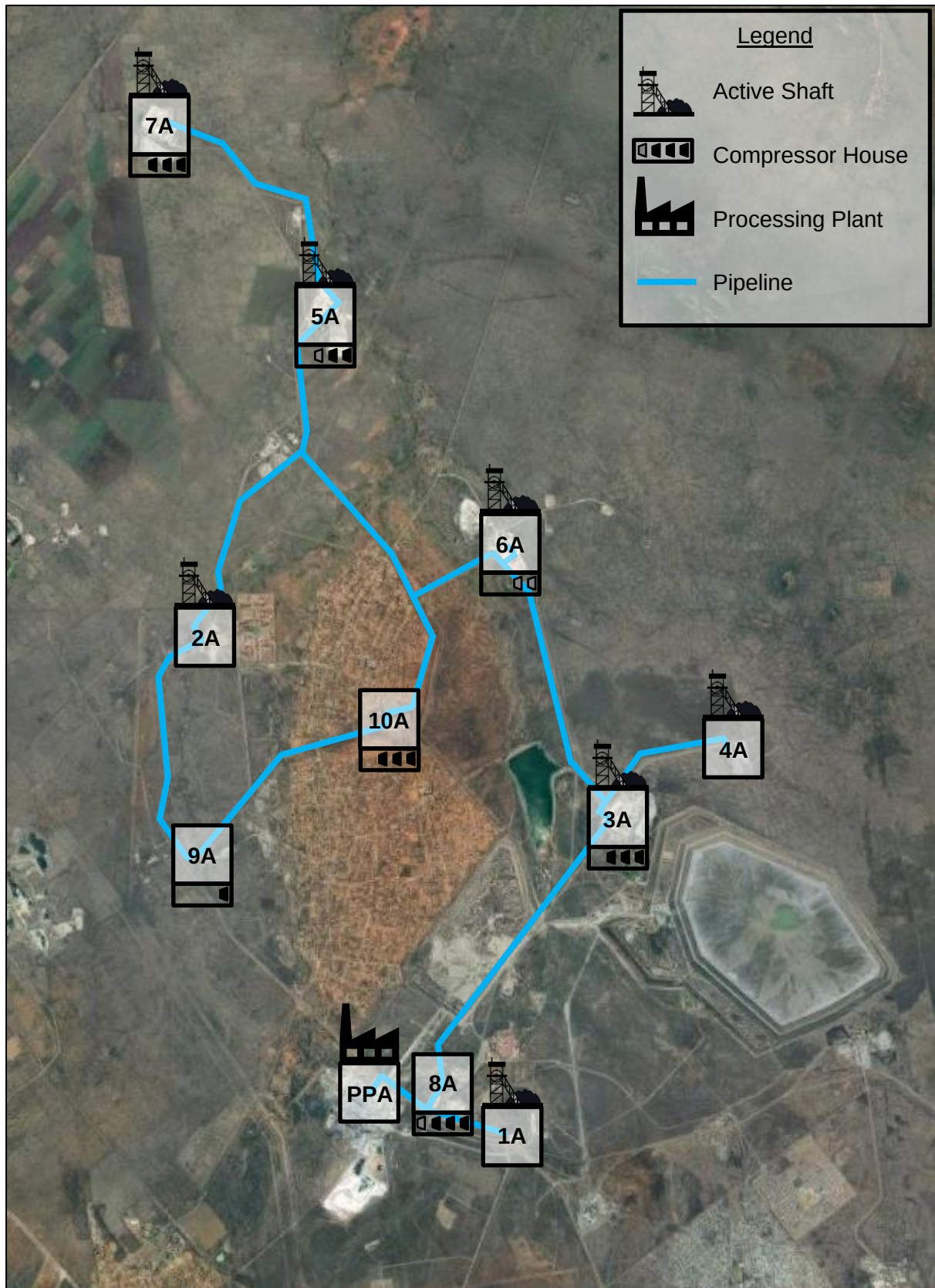


Figure 3-1: System A-1 satellite image

The individual efficiencies of the compressors could unfortunately not be calculated accurately due to insufficient and unreliable data. The locations of the various suppliers and individual compressors with their capacities are summarised in Table 3-1.

The consumers on the system were identified and their locations provided in Figure 3-1. Only one consumer used active valve control at the time. Although the three shafts at 2A, 4A, and 6A each had some form of control valve installed, only 6A was actively controlling. The various demands are also summarised in Table 3-1.

Table 3-1: System A-1 demands and suppliers

Facilities	Demands	Suppliers	Compressors
PPA	Processing Plant A	–	–
1A	Shaft 1A	–	–
2A	Shaft 2A	–	–
3A	Shaft 3A	Compressor House 3A	3 × VK32
4A	Shaft 4A	–	–
5A	Shaft 5A	Compressor House 5A	1 × VK50; 2 × VK32
6A	Shaft 6A	Compressor House 6A	2 × VK50
7A	Shaft 7A	Compressor House 7A	3 × VK32
8A	–	Compressor House 8A	3 × VK32; 1 × VK50
9A	–	Compressor House 9A	1 × VK32
10A	–	Compressor House 10A	3 × VK32

It is important to note that Shaft 3A only became an independent demand early in 2019 when it was separated from the Shaft 4A subsystems. The impact of this change was accounted for with a non-routine baseline adjustment as shown in Section 3.2.2.1 of this chapter.

The consumer pressure requirements are discussed later in Section 3.2.1.2 when determined as needed for the selected strategies. Furthermore, the system infrastructure, data, and

software limitations are also investigated further in Section 3.2.1.2 when the strategies are compared to determine the operational requirements and implementation strategies.

Operational schedules

System A-1 used the same three primary shifts and similar intermediate periods as described in Section 2.2.1.2. The shifts and their respective intervals are shown in Table 3-2.

Table 3-2: System A-1 operational schedule

Shifts/periods	Start times	End times
Cleaning shift	22:00	04:00
Morning reduction (shift change)	04:00	06:00
Drilling shift	06:00	14:00
Afternoon reduction (explosive charge-up)	14:00	18:00
Blasting shift	18:00	21:00
Night reduction (shift change)	21:00	22:00

The schedule is shown in Figure 3-2 with a typical total power profile for the compressors.

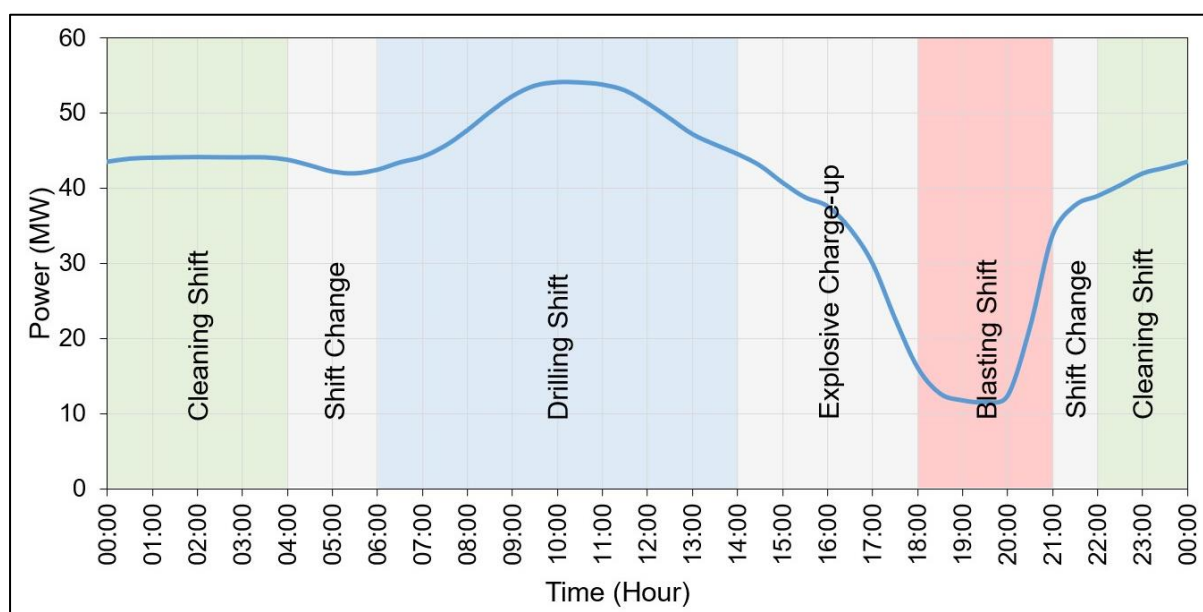


Figure 3-2: System A-1 typical compressor power demand profile and schedule

The profile peaked during the drilling shift when the most compressors were started. During the drilling shift, the system typically operated at full capacity with all nineteen compressors in use. This left no room for demand expansion without compromising the supplied pressures.

The lowest point on the profile occurred during the blasting shift when the fewest compressors were in use. During the blasting shift, the use of one VK50 and three VK32 compressors was often the standard arrangement. These compressors ensured that the essential systems at the shafts and all systems at the processing plant received adequate compressed air supply.

3.2.1.2 Operational requirements

Applying the methodology developed in Section 2.3, the first actionable task is to determine what strategies can be implemented fully. Once these strategies have been identified, the strategies that follow those to be implemented fully can be considered for principle-based implementation. The strategies identified to undergo principle-based implementation and the specific alternative strategy to do so can then be identified.

Determine implementation strategies

The strategies to be implemented fully must first be identified by considering both the infrastructure and data requirements of each strategy. This was done for System A-1 and the investigation outcome is summarised in Table 3-3. This table was developed from Table 2-4.

Table 3-3: System A-1 strategies full implementation checks

Strategies	Infrastructure	Data	Completeness	Incomplete items
Valve control	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves
Guide vane control	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Systems out of date and need repair
Compressor schedules	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Insufficient and unreliable data
Automation of compressed air control	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, functional systems, and required data

The investigation rendered a null result as no strategies could be implemented fully due to the lack of required infrastructure and data. Considering the first strategy, although three shafts had control valves installed, valve control could not be implemented effectively across the system for the reasons shown in Table 3-4.

Table 3-4: System A-1 valve control full implementation checks

Consumers	Infrastructure	Data	Incomplete items
PPA	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
1A	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
2A	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of measurement instrumentation and data
3A	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
4A	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of measurement instrumentation and data
5A	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
6A	☒ Complete ☐ Incomplete	☒ Complete ☐ Incomplete	Central control software requires upgrades to control valve network
7A	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data

The control valve installed at Shaft 6A had been active since early 2018 as the mine was testing the use of control valves. Although the implementation was limited, it had the potential to implement valve control fully with only a few months' delay.

However, to create a meaningful impact on the system, the requirement for principle-based implementation of valve control persisted regardless of whether full valve control was implemented at Shaft 6A or not. Without principle-based implementation thereof, the delay and the lack of control on the other shafts would have generated significant missed opportunities.

As no strategies could be implemented fully and valve control is the first strategy in the principle-based implementation table (Table 2-5), further investigation was carried out to identify which alternative strategies were possible. The outcome of the investigation is summarised in Table 3-5. This table was developed based on Table 2-5.

Table 3-5: System A-1 valve control principle-based implementation checks

Strategies	Infrastructure	Data	Implementation
Valve control	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete

The earlier investigation to identify strategies for full implementation simplified the latest investigation significantly. As the investigation had already eliminated all the automated control based strategies, only manual network control had to be investigated, which produced a positive result. Manual network control was possible on System A-1. The complete and summarised results for the investigations are shown in the elimination rubric of Table 3-6. This table was developed based on Table 2-6.

Table 3-6: System A-1 strategies elimination rubric

Strategies	Full	Principle	Implementation	Principle strategy
Valve control	☐ Complete ☒ Incomplete	☒ Complete ☐ Incomplete ☐ N/A	☐ Full ☒ Principle ☐ None	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete ☐ N/A
Guide vane control	☐ Complete ☒ Incomplete	☐ Complete ☐ Incomplete ☒ N/A	☐ Full ☐ Principle ☒ None	☐ MNC complete ☐ CS complete ☐ All incomplete ☒ N/A
Compressor schedules	☐ Complete ☒ Incomplete	☐ Complete ☐ Incomplete ☒ N/A	☐ Full ☐ Principle ☒ None	☐ MNC complete ☐ All incomplete ☒ N/A
Automation of compressed air control	☐ Complete ☒ Incomplete	N/A	☐ Full ☒ None	N/A

Once the strategy was identified, focus could shift to determining the control targets.

Determine control targets

As manual network control was identified as the principle-based implementation strategy for valve control, surface pressure targets had to be determined for the system. Control room operators could then stop and start compressors to meet these pressure requirements. The pressure requirements were first determined by historical data analysis, whereafter they were checked and adjusted according to end user requirements. Finally, the pressure requirements were adjusted once more according to specifications given by the responsible demand-side engineers.

Historical data analysis was used to produce frequency plots (Figure 3-3) and average full-day demand-side pressure profiles (Figure 3-4) for each consumer on the system. However,

the figures shown were produced with the average demand pressures of all the consumers on System A-1 to show the process followed and any requirements or improvements overall.

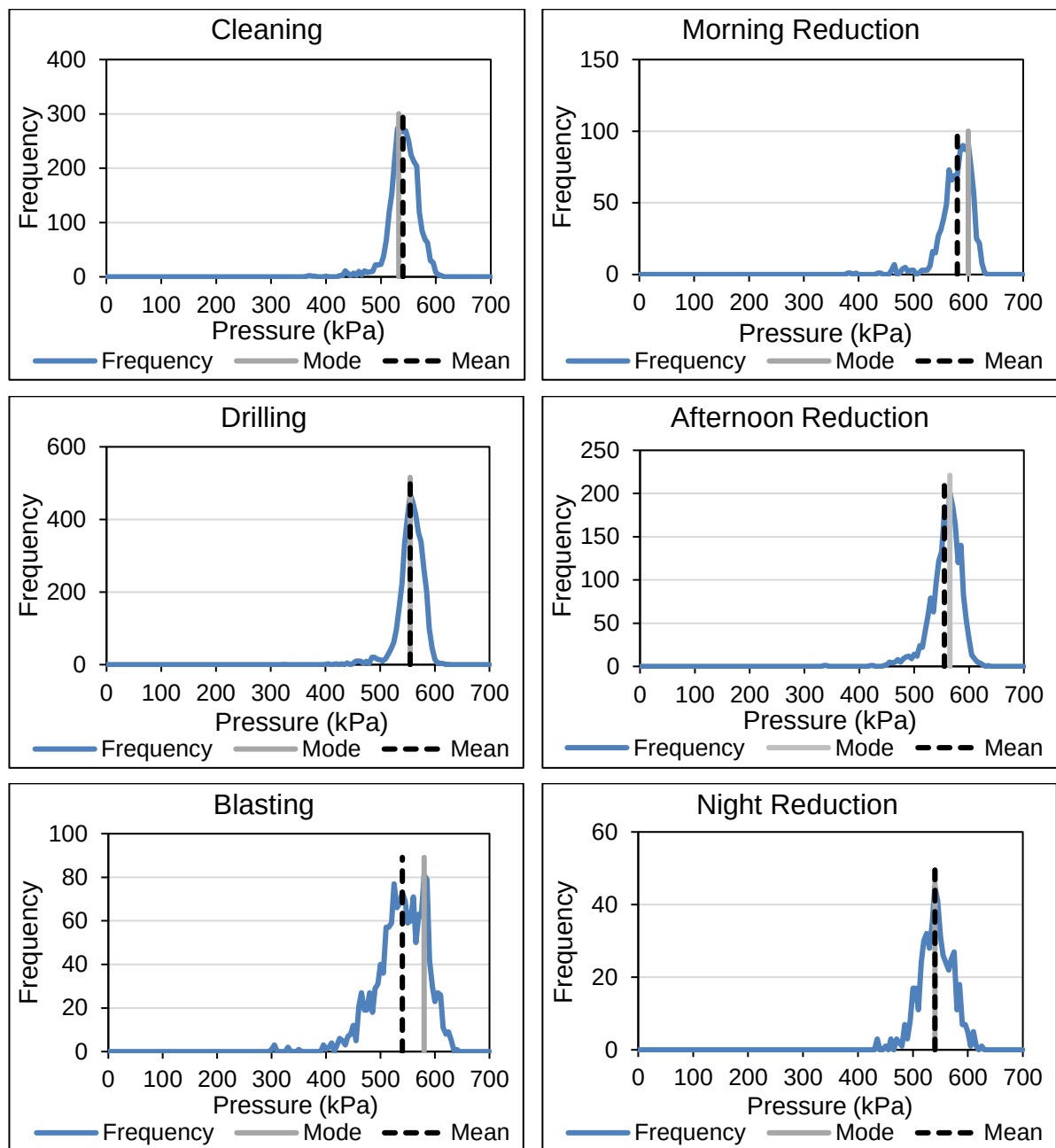


Figure 3-3: System A-1 pressure distribution per shift

The historical data analysis considered the full year (2018 to 2019) period preceding implementation as the baseline period in order to account for any seasonal effects and later investigate the rate of system growth. Any instances in this period where unusual activities occurred that would affect the accuracy of the baselines and targets were excluded.

The set of graphs in Figure 3-3 show the frequency plots for the average demand pressures for the whole of System A-1 in the form of normal ("bell-shaped") and non-normal distributions

for each shift from Table 3-2. The mode and mean pressure values for each of the shifts are also shown.

Differences between the mode and mean values for the non-normal distributions were due to transient pressures at the start or end of a shift. Why the mode gravitates to the transient values is simply due to consistency. The actual shift pressures continuously vary day-to-day while the transient pressures always pass through the same values while going from low-to-high or high-to-low pressures. This caused the mode value to be more volatile as any transient values would skew the mode. Furthermore, the greater the difference between the shift pressures where transience occurred, the greater the mode value was skewed. The mean values did not experience such issues.

As the mean values provided more stable and representative values of the normal demand pressures, they were used to develop the initial pressure target profiles. The average full-day demand pressure profile for System A-1 is shown in Figure 3-4 along with the profiles developed by the mean and mode pressure values determined.

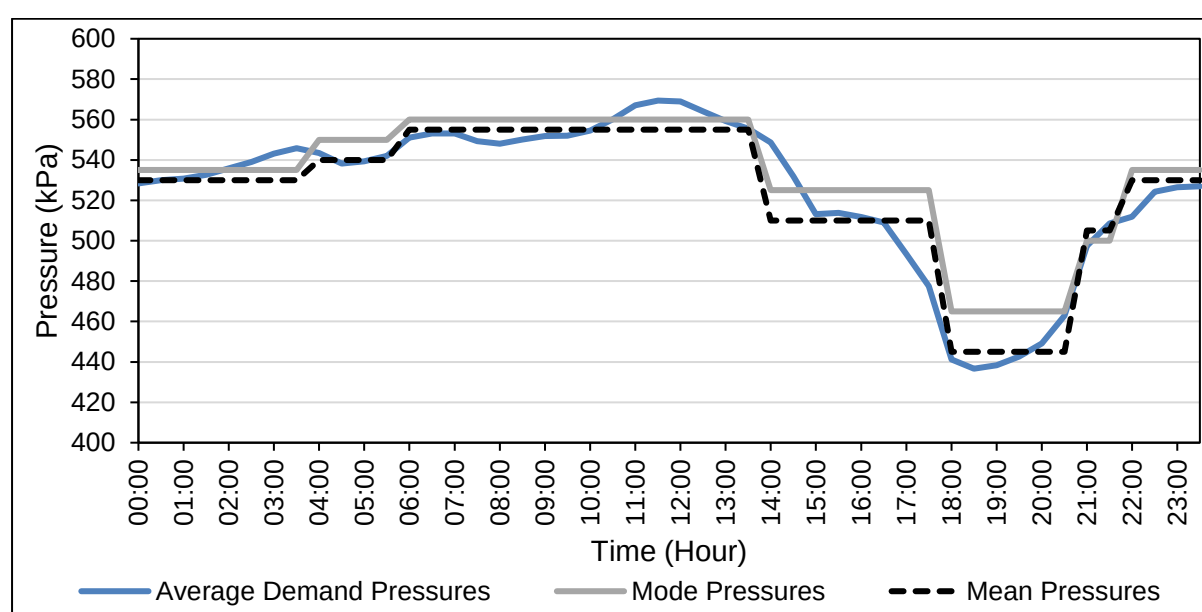


Figure 3-4: System A-1 demand pressure profiles

The same curves were plotted for each consumer on the system and were used to determine the individual targets shown in Table 3-7. The only exception was Shaft 4A as it did not have data for 2018. This shaft was part of the Shaft 3A system until March 2019 when the 4A systems were separated from 3A.

The mean frequency pressure values for each shift and for each consumer are summarised in Table 3-7 in kilopascal. These pressures represent the starting pressure targets that were refined further as limitations were identified.

Table 3-7: Starting pressure targets for each demand on System A-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
PPA	600	610	600	590	590	595
1A	605	605	590	585	560	585
2A	545	585	565	555	540	545
3A	520	555	525	545	535	535
4A	520	555	525	545	535	535
5A	555	590	585	565	545	550
6A	505	395	550	330	185	345
7A	550	580	570	560	535	535

As Shaft 4A did not exist independently of Shaft 3A during the baseline period, the starting pressure targets for Shaft 3A were simply used for Shaft 4A as well.

The most extensive collection of equipment that could be used during each shift according to Section 1.2.4 was identified for the shafts. The corresponding average pressure requirements in kilopascal are summarised in Table 3-8. The piece of equipment with the highest average pressure requirement during a particular shift determines the overall pressure requirement for that shift.

Table 3-8: System A-1 demand-side operations pressure requirements per shift

Demand-side operations	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
Rock drills	–	–	510	–	–	–
Venturi blowers	485	485	485	485	–	485
Mechanical ore loaders	450	–	–	–	–	–
Diamond drills	500	–	500	–	–	–
Refuge bays	250	250	250	250	250	250
Rock breakers	450	–	–	–	–	–
Loading boxes	475	–	–	–	–	–
Blow pipes	375	375	375	375	–	375
Pneumatic cylinders	475	475	–	475	–	475
Agitators	400	400	400	400	400	400
Other instrumentation	475	475	475	475	475	475

Using the maximum end user equipment pressure requirement for each shift, the shaft pressure requirements in kilopascal were set as shown in Table 3-9.

Table 3-9: System A-1 shafts' equipment maximum pressure requirements per shift

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
All shafts	500	485	510	485	475	485

The starting pressure targets for the shafts were adjusted to be equal to the shaft pressure requirements only where the starting pressure targets were greater than the pressure requirements. The adjusted starting pressure targets are shown in Table 3-10 in kilopascal.

Table 3-10: Adjusted starting pressure targets for each demand on System A-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
PPA	600	610	600	590	590	595
1A	500	485	510	485	475	485
2A	500	485	510	485	475	485
3A	500	485	510	485	475	485
4A	500	485	510	485	475	485
5A	500	485	510	485	475	485
6A	500	395	510	330	185	345
7A	500	485	510	485	475	485

Due to autocompression, the demand pressure requirements on surface could be less than those of the end users as shown in Table 3-9. However, due to the underground dynamics of each shaft being unique, simply calculating for static autocompression would not provide accurate real-world results. Therefore, each demand-side engineer was consulted and assisted to adapt the starting pressure targets further according to their expected pressure variations and particular requirements unique to their shaft. These final adaptations made to the starting pressure targets produced the goal pressure targets as in kilopascal in Table 3-11.

Table 3-11: Goal pressure targets for each demand on System A-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
PPA	600	590	600	590	590	590
1A	490	560	585	560	560	560
2A	490	470	580	470	440	445
3A	470	470	550	470	440	445
4A	485	470	520	470	440	445
5A	490	470	595	470	440	445
6A	480	470	545	470	440	445
7A	495	470	575	470	440	445

Both the 2018 baseline supply pressures and the goal pressure targets for System A-1 are shown in Figure 3-5, clearly indicating where pressure reductions were expected. After implementation, the pressures were controlled as close to the goal pressure targets of each demand as possible. How accurately the pressures were controlled depended on the specific constraints experienced on the dynamic system on a day-to-day basis. The entire process to determine the goal pressure targets was repeated on a monthly basis to ensure the pressure targets met any changing demand requirements. Only minor adjustments were required occasionally.

It is later shown in Section 3.2.2.4 that the implementation encountered significant constraints in reality that resulted in elevated pressure targets being used. For this reason, as stipulated in Section 2.5.3, the pressure targets had to be adjusted to produce accurate theoretical energy improvement values. The adjusted pressure targets are shown in Table 3-12.

Table 3-12: Adjusted pressure targets for each demand on System A-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
PPA	595	600	600	595	595	595
1A	550	565	585	555	535	540
2A	505	545	580	545	525	510
3A	480	505	550	525	525	490
4A	455	480	520	515	530	475
5A	515	555	595	555	520	515
6A	500	535	545	550	535	515
7A	500	535	575	545	520	500

Since control was not implemented during the drilling shift, the target pressures were not adjusted during this period. The adjusted pressure targets for System A-1 are also shown in Figure 3-5.

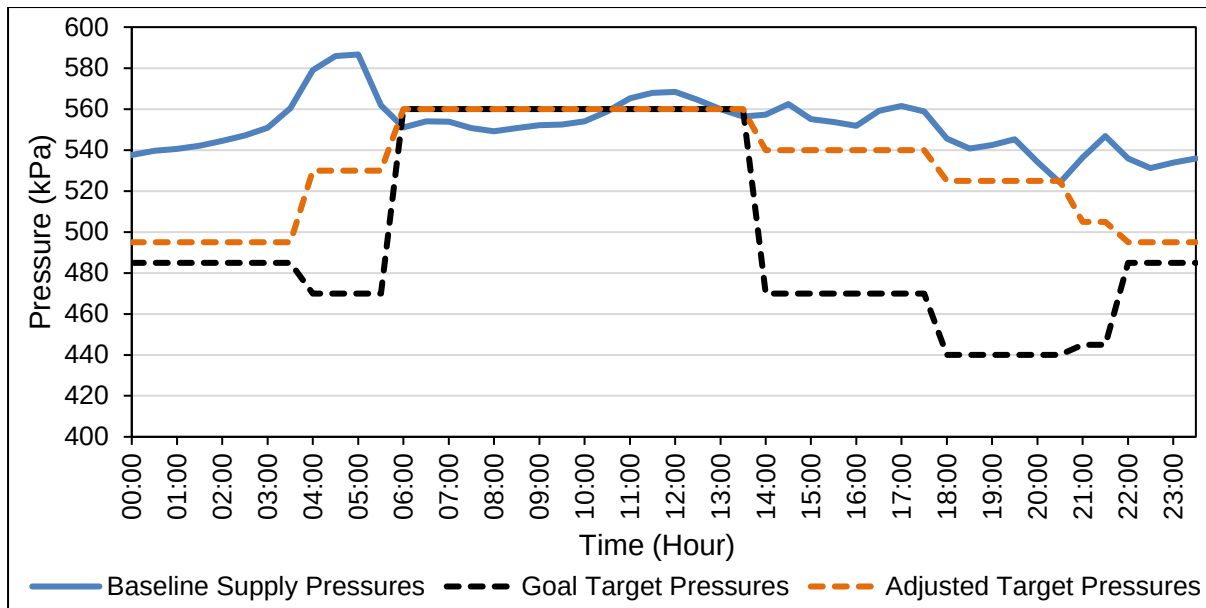


Figure 3-5: System A-1 baseline and target supply pressure profiles

The adjusted pressure targets, henceforth referred to as the theoretical pressures or simply the target pressures, were further used to calculate the theoretical values.

3.2.1.3 Implementation

As outlined in Section 2.4, the control requirements and implementation strategy were considered first followed by monitoring.

Control

The first step was to establish the control required, followed by how it would be implemented. As the only strategy being implemented was manual network control, the only control required was stopping and starting compressors to meet pressure requirements. There were no variations to this strategy regarding controlling principles or parameters.

The implementation of control was primarily dependent on the system software and the mine's IT policies. On System A-1, the only control software available at the time was a SCADA that was shared with System B-1 from the next case study. IT policies prohibited changes to the programming of the SCADA to utilise further functions thereof for the purposes of this study. The control room operators could, however, view system pressures, available compressors, and all parameters needed for the control. The SCADA system used is shown in Figure 3-6.

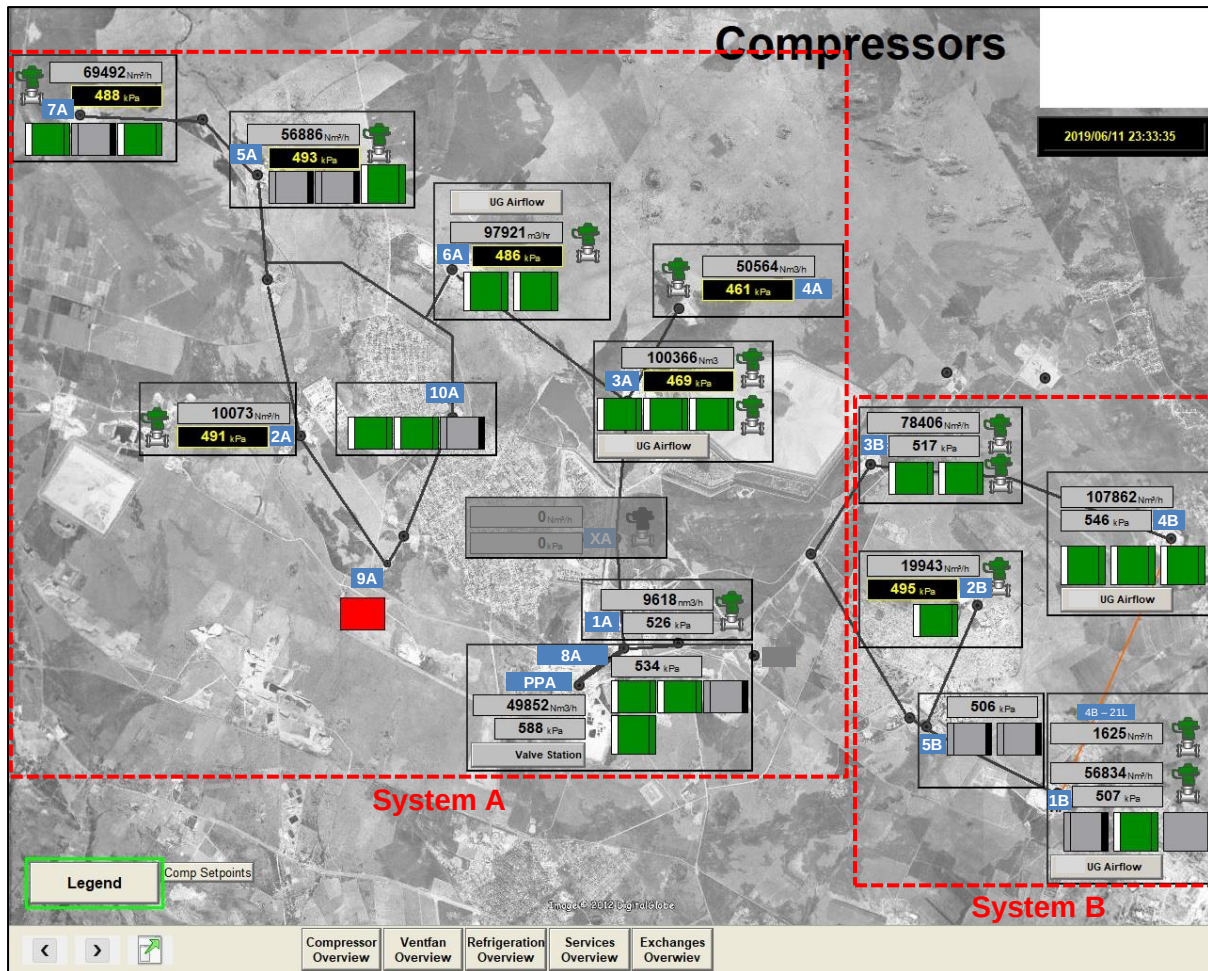


Figure 3-6: System A and System B shared SCADA

Figure 3-6 indicates the surface pressure and demand flow for each demand, with the surface pressures being the primary control parameters. The available compressors and their statuses are shown for each compressor house. Compressor status is indicated by the colour of the individual unit displayed. The compressor status indicators are summarised in Table 3-13.

Table 3-13: System A-1 compressor status indicators

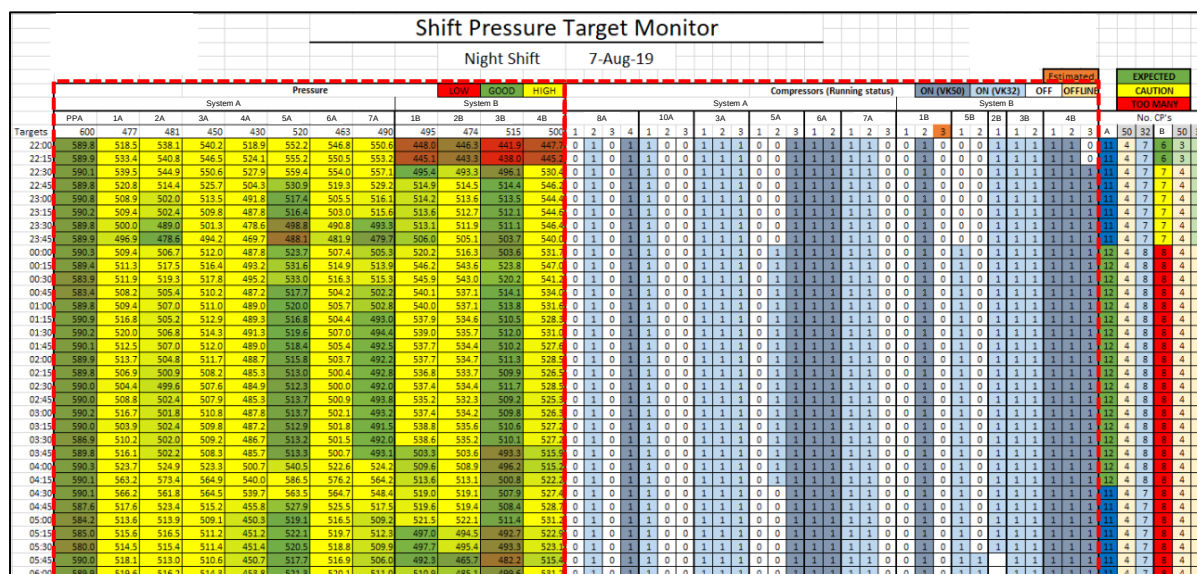
Indicators	Status
Green pulsing	Start-up sequence active
Red solid	Compressor drive trip
Green solid	Compressor drive run
Black pulsing	Shutdown sequence active
Blue solid	Compressor drive running down
Grey solid	Compressor drive stopped (ready to start)

Due to the availability of these systems, manual network control could be implemented.

Monitoring

As with control, the required monitoring is identified first. For this project, the control parameters had to be monitored to ensure the pressures were maintained close to the targets. Ideally, the pressure targets were to be programmed into the SCADA system as the SCADA provides an indicator feature that flags any pressure that exceeds its target. However, the mine's IT policies did not allow this.

Therefore, the implementation strategy for the required monitoring focused on a simple external system. Initially, implementation was purely manual with targets provided to the operators on printed sheets of paper, but this was tedious and later digitised by the author in a Microsoft Excel workbook. The Excel-based dashboard pulled live data through the historian, compared it with the respective targets, and indicated deviations that required the operators' attention. The developed Excel dashboard used for both System A-1 and System B-1 is shown in Figure 3-7.



unavailable at the time. The total number of running compressors is shown in the far right columns and indicates when they exceeded the expected number of compressors at any given time.

As the control room operators worked in eight-hour shifts, the dashboard could toggle between the different shifts to limit the amount of data being processed at any given time. This limited the load on both the control room computers and the local data network.

The monitoring of energy savings was done manually on a monthly basis. The energy and cost savings realised are discussed further in the next section.

3.2.2 Results

3.2.2.1 Development of baselines and theoretical values

The methods discussed in Section 2.5 were used to develop the necessary baselines and adjustment techniques for determining the solution savings.

Baseline development

The power baseline was developed for weekdays from the year 2018 prior to the implementation of the developed solution in 2019. As the baseline methods stipulated, the power baseline underwent a routine baseline adjustment by scaling it daily according to the peak drilling period consumption.

In order to account for permanent demand changes during the peak drilling period between 2018 and 2019 that required corrections to the power baseline scaling, the compressed air pressure and flow baselines were developed. These baselines were also used to calculate the theoretical savings. Furthermore, the KPIs and specific power baseline profiles from 2018 had to be determined for baseline adjustment and theoretical value calculation purposes. All developed baselines feature in the relevant figures later in this chapter.

Non-routine baseline adjustments

As the compressor supply network on System A-1 was running at full capacity during the peak drilling period in 2018, it was necessary to ensure that the supply/demand balance had not changed significantly due to permanent system changes in 2019. A permanent demand increase during the peak drilling period would have caused the control room operators to start additional compressors to maintain baseline pressures. However, as there were no more available compressors to start, this would hinder the routine baseline scaling in its ability to

provide an accurate would-have-been representation of operations outside the peak drilling period during which additional compressors were still available. In such a case, the incoming power data would have to be manipulated artificially to provide a more accurate representation of the would-have-been scenario. The impact of the reconfiguration and expansion of activities on the 3A and 4A systems at the end of March of 2019 were a cause for concern in this regard.

In order to determine the adapted demand flow and power profiles, the system demand KPI for early 2019 had to be investigated. The KPI trend was investigated for when the 3A and 4A systems separated to determine the impact thereof. The daily average KPI value trend for 2019 on System A-1 excluding the Easter holiday and December break periods is shown in Figure 3-8.

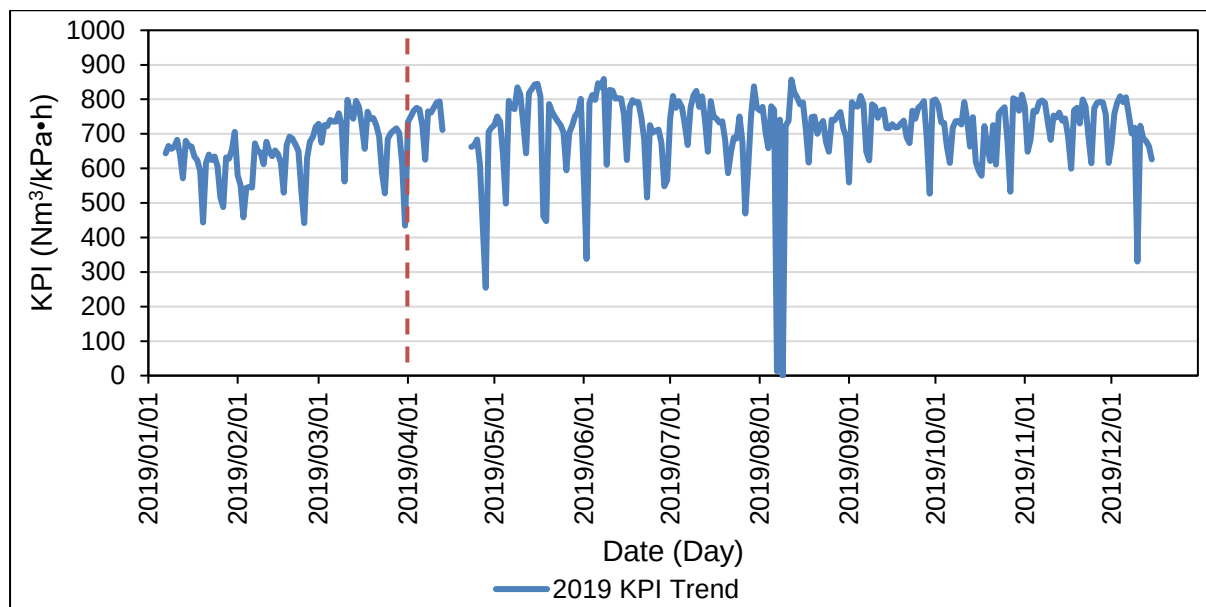


Figure 3-8: System A-1 2019 demand KPI trend

The work done to separate the 3A and 4A system as well as maintenance carried out on three other shafts elevated the average KPI values during March. Therefore, when the system change occurred on 1 April 2019, as indicated, the step change in the KPI value was not well defined. The average KPI value prior to the change was $665 \text{ Nm}^3/\text{kPa}\cdot\text{h}$ and increased by 6.8% to $710 \text{ Nm}^3/\text{kPa}\cdot\text{h}$ after the change. The developed KPI baseline profile from 2018 and the percentage increase $c_1 = 6.8\%$ were used in Equation 2-4 to determine this projected KPI for the 2019 system change. The new projected KPI was calculated to account for the increase caused by the system change and is thus only representative of the system change that occurred. As this new KPI is only representative of the system change and not the total projected KPI, it is referred to as the adapted KPI profile. Both the KPI baseline profile and the adapted KPI profile for 2019 are shown in Figure 3-9.

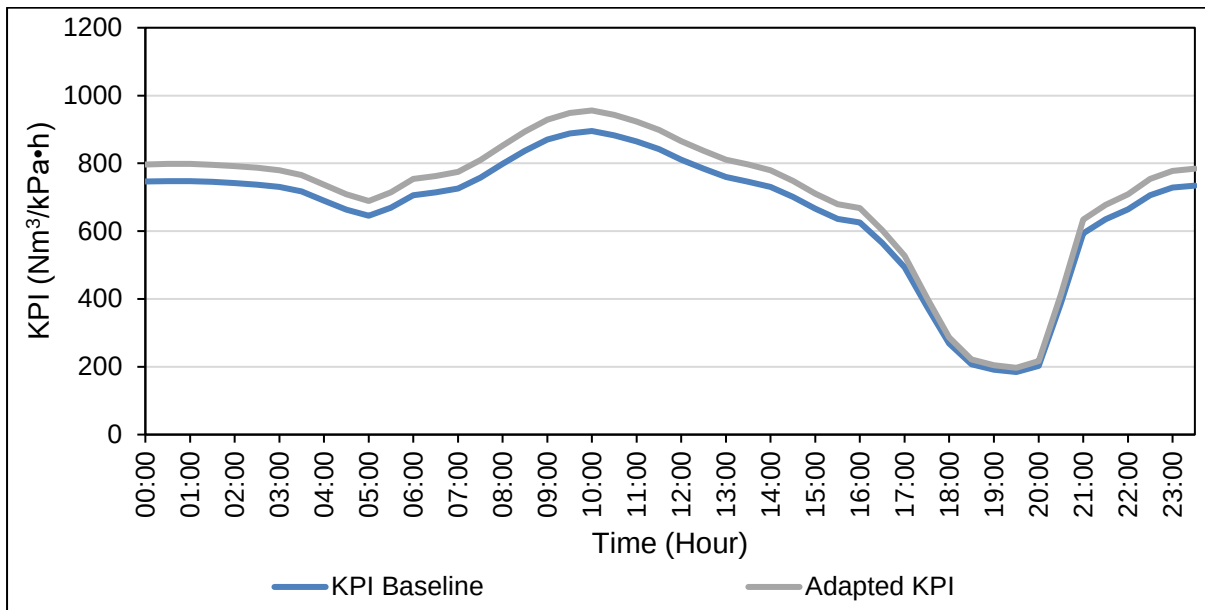


Figure 3-9: System A-1 KPI baseline and adapted KPI

By multiplying the pressure baseline and the adapted KPI profile (refer to Equation 2-5), the adapted demand flow was determined. This adapted demand flow for 2019 and the demand flow baseline are both shown in Figure 3-10.

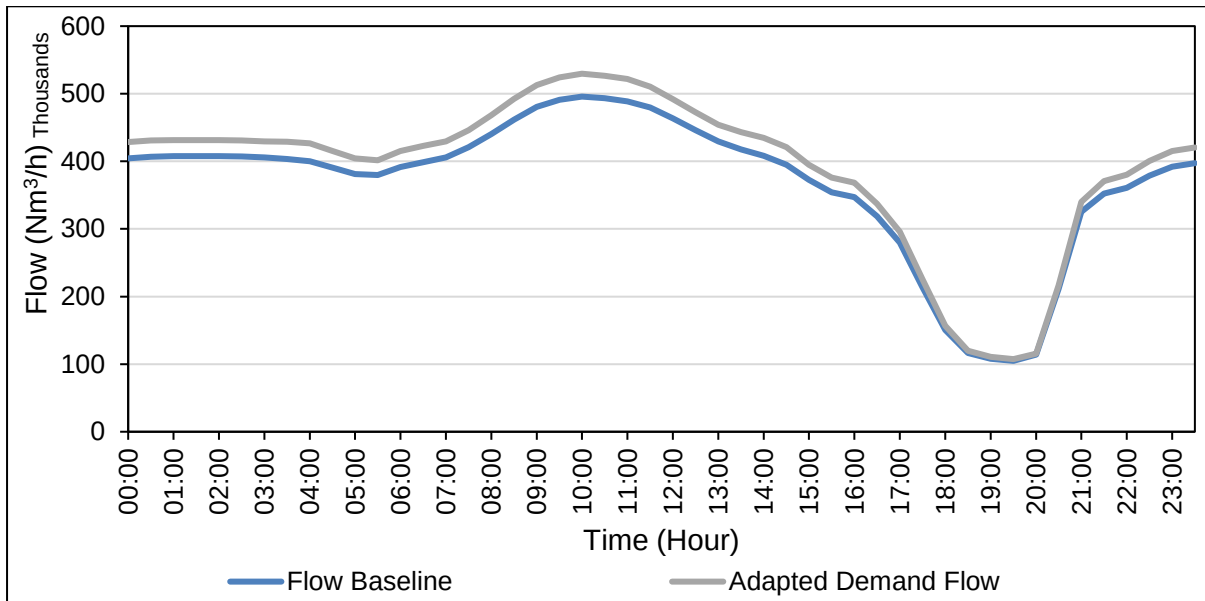


Figure 3-10: System A-1 demand flow baseline and adapted demand flow

The adapted flow demand increased over the baseline during the peak drilling period with an average of 29 900 Nm³/h. This increase was 113% of the average discharge flow capacity of one of the VK32 compressors and 69% of one of the VK50 compressors. It could, therefore, be assumed that should the compressors have been available, an additional VK32

compressor would have been started during the peak drilling period to maintain pressures similar to those of the baseline.

It was decided that the power capacity of a single VK32 compressor should be added to the actual power profile during the peak of the drilling shift. The addition of the VK32 power capacity was possible as the project did not aim to reduce pressures during the peak drilling period to avoid affecting production. This was further necessary to produce an accurate would-have-been representation of the power profile as the routine baseline adjustment only scaled according to the actual power during the peak period.

Since the project started in April 2019, the average actual flow demand profile observed for 2019 was recorded. The average actual, adapted, and baseline flow demand profiles are shown in Figure 3-11.

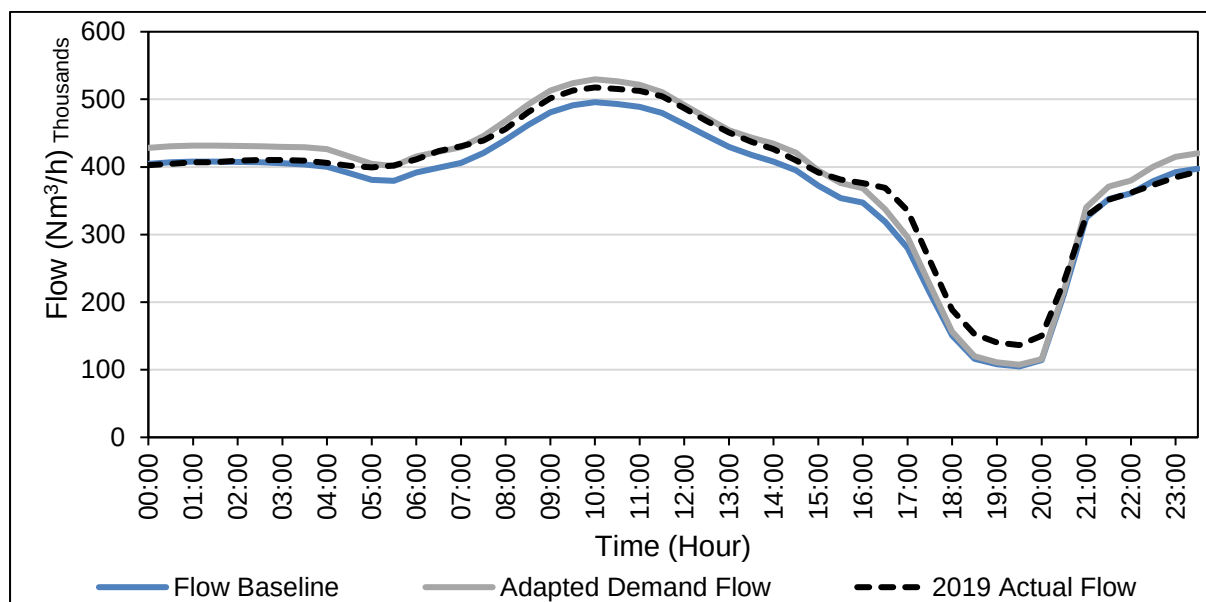


Figure 3-11: System A-1 2019 actual demand flow comparison to baseline and adapted flows

This comparison made it apparent that the total demand during the peak drilling period on System A-1 had increased in 2019 as expected. As the supply network had already been running at full capacity, this demand could not have been met without resulting in reduced pressures during the drilling shift as shown in Figure 3-12. As the manual network control implemented in 2019 was not active during the drilling shift, any pressure reductions between 06:00 and 14:00 in 2019 were the result of the limited supply capacity on the system.

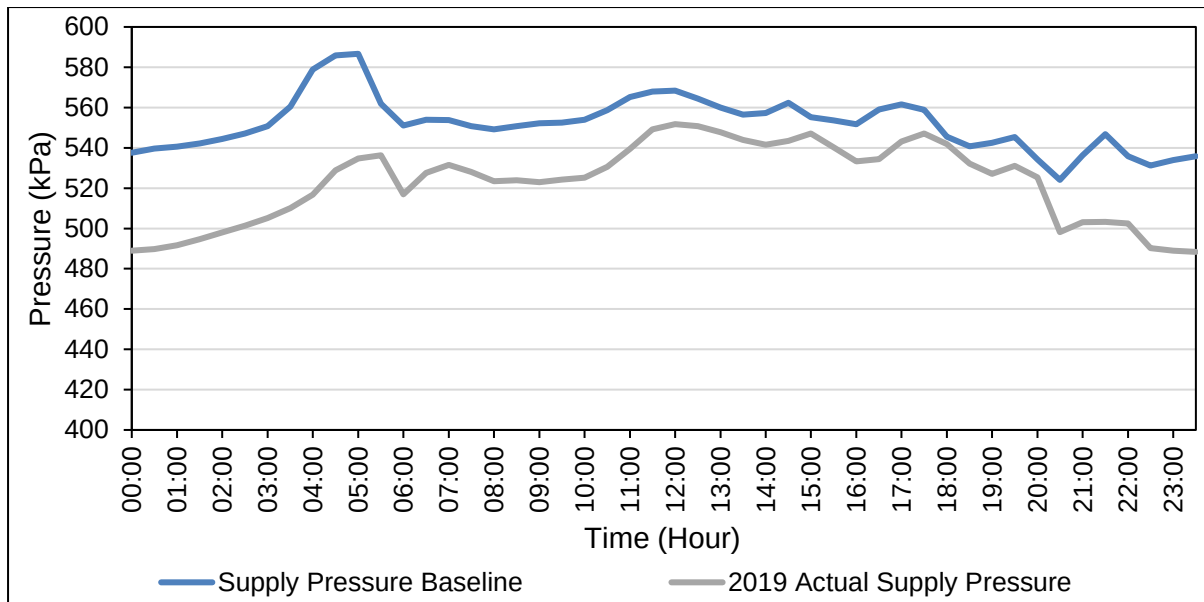


Figure 3-12: System A-1 2019 actual supply pressure comparison to baseline supply pressure

Although the average system pressure reduction between 06:00 and 14:00 was relatively small at 27.2 kPa, this was the average pressure change across an extensive system. Some demands experienced more extreme pressure reductions while others experienced less extreme pressure reductions. The total impact of the pressure reduction thus scaled significantly due to the size of System A-1. Finally, these flow and pressure observations confirmed that the decision made regarding the need for a non-routine baseline adjustment with the added capacity of a single VK32 compressor was justified and accurate.

Calculation of theoretical values

In order to motivate the implementation and verify the solution, the theoretical potential savings had to be determined first. As this study only sought to implement projects that required no capital investment, no payback period was considered and savings were rendered immediately.

The 2019 adapted KPI profile was used to determine the potential energy and cost savings for the study. However, the adapted KPI profile first had to be adjusted further to consider the expected average year-on-year base KPI increase due to system expansion and further leak and inefficiency growth on the demand-side. The 2018 daily average base KPI trend excluding the December break periods is shown in Figure 3-13, which shows a 5.1% increase over the period.

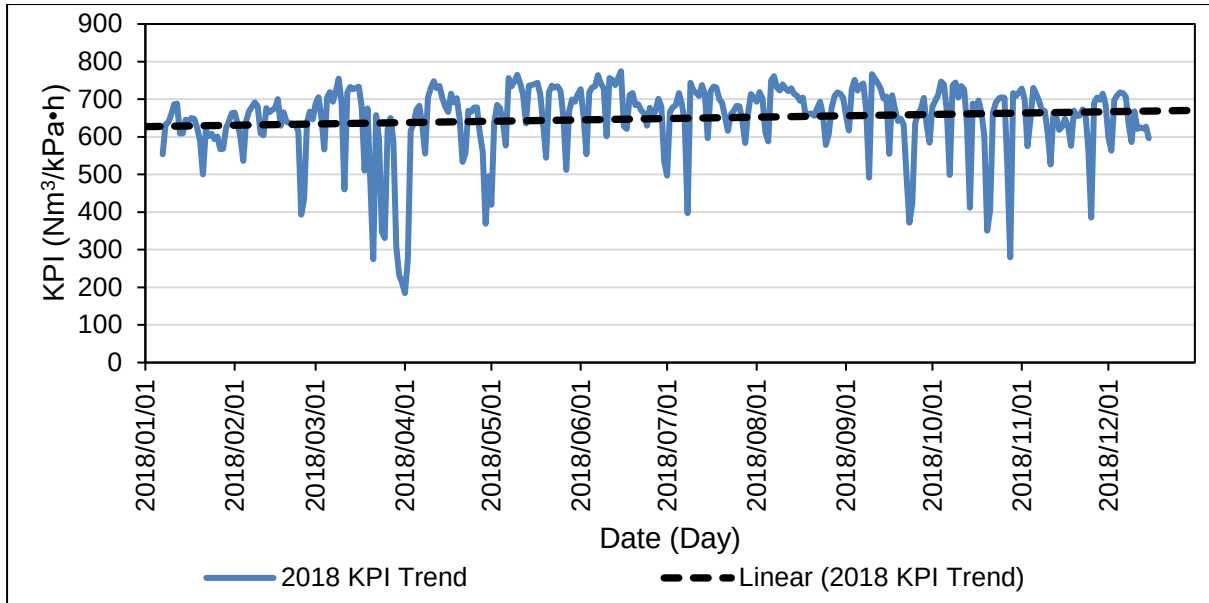


Figure 3-13: System A-1 2018 demand KPI trend

It was assumed that in 2019 the system base KPI would follow a similar upward trend of 5.1% over the year period. This base KPI increase was thus used to further scale up the existing adapted KPI. This was done by using the KPI baseline, the c_1 increase value from the adapted KPI, and $c_2 = 5.1\%$ in Equation 2-4. This newly adjusted KPI profile represents the total 2019 KPI and is thus referred to as the 2019 projected KPI profile. The baseline and projected KPI profiles are shown in Figure 3-14.

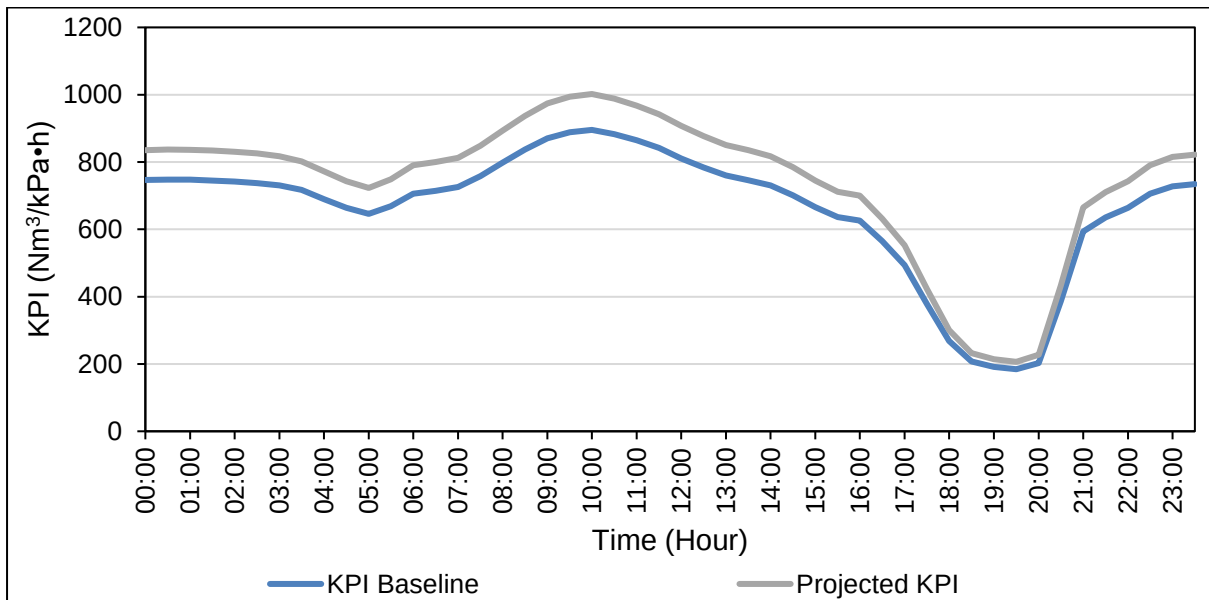


Figure 3-14: System A-1 KPI baseline and projected KPI

The 2019 theoretical specific power profile was calculated by means of Equation 2-7. Both the baseline and theoretical specific power profiles are shown in Figure 3-15.

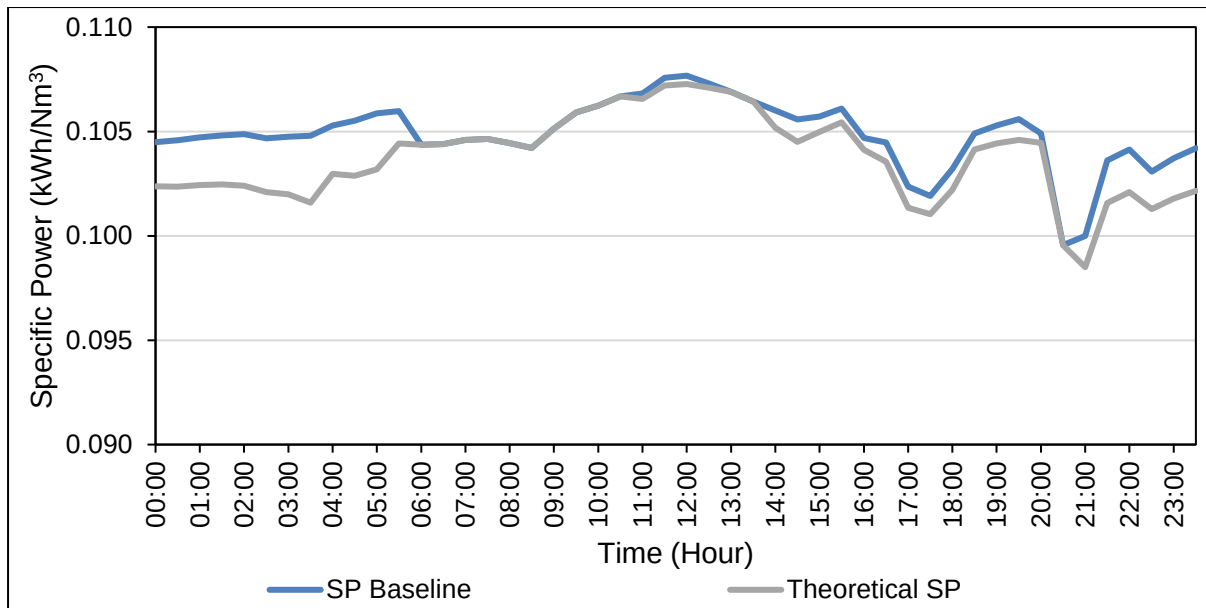


Figure 3-15: System A-1 specific power baseline and theoretical specific power

Both the 2019 projected flow and theoretical flow profiles were calculated with Equation 2-5 using the appropriate inputs provided. These flow profiles are available in Appendix A. The corresponding power profiles were produced by applying Equation 2-8 and the relevant inputs shown for the projected and theoretical profiles, respectively. The theoretical power savings for the supply- and demand-side systems and their supplied inputs were also calculated with Equation 2-8. Both the 2019 projected power and theoretical power profiles are shown in Figure 3-16 along with the individual contributing supply- and demand-side power savings. The data for the projected and theoretical profiles is available in tabular form in Appendix B.

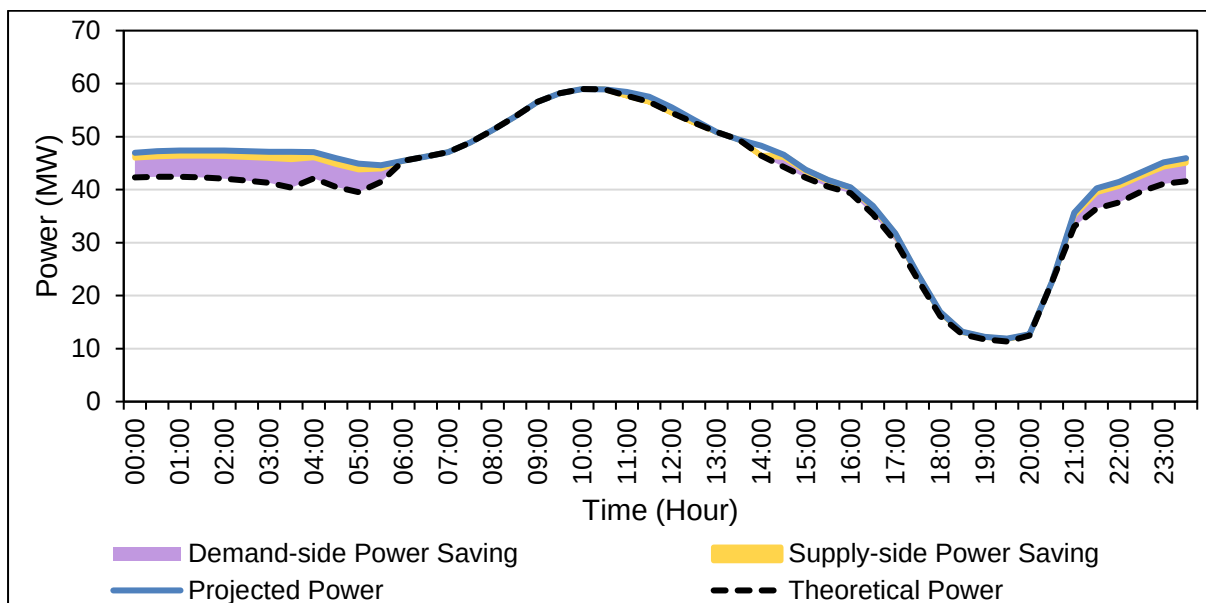


Figure 3-16: System A-1 projected and theoretical power profiles

The potential energy saving was calculated by taking the difference between the projected and theoretical power profiles and multiplying that difference by the measurement interval at each time step as shown in Equation 2-10. Thereafter, the individual values were summed to provide the daily potential energy saving. Each value was further multiplied by the respective Eskom TOU rate to determine the daily potential cost saving both for summer and winter. Extrapolating the daily potential savings for both seasons produced theoretical annual energy and cost savings of 9.9 GWh and R6.8 million, respectively, at 2018–2019 Eskom rates (R9.3 million – 2022 Eskom rates). The total theoretical saving was divided between the contributors, the supply- and demand-side systems, by 19.7% and 80.3%, respectively.

3.2.2.2 Calculation of energy improvement

As shown in Figure 3-17, the actual daily energy savings were calculated by taking the difference between the scaled baseline and actual power profile (remembering to make the identified non-routine adjustments), multiplying by the measurement interval, and summing the values. The energy savings were used to calculate the cost savings using the same method as before while remembering to account for the Eskom TOU electricity tariffs.

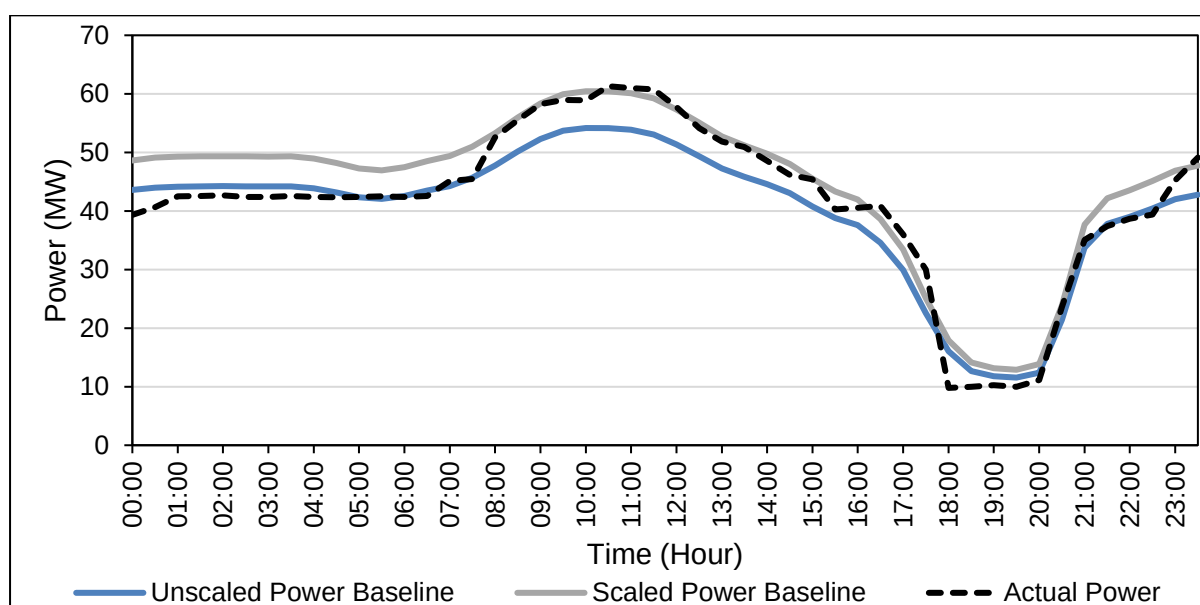


Figure 3-17: System A-1 power baseline scaling example

The energy and cost savings were calculated and recorded from the start of the project in April 2019. By the end of December 2019, the project had accumulated 8.1 GWh and R5.4 million (R7.4 million – 2022 Eskom rates) in energy and cost savings, respectively. The savings were further recorded until 12 months had passed. At the end of March 2020, cumulative savings of 10.0 GWh and R6.6 million (R9.0 million – 2022 Eskom rates) had been realised.

3.2.2.3 Verification of solution

The accuracy of the developed solution was verified using Equation 2-11. The theoretical annual energy savings provided at the end of Section 3.2.2.1 had fallen short of the actual savings by only 0.8%, while the annual cost savings target overestimated by only 2.4%. The fact that the theoretical energy savings showed a less significant deviation or error than the theoretical cost savings indicates that energy savings realised during low-tariff periods exceeded expectation, while energy savings realised during high-tariff periods were less than expected. Nonetheless, as the error values calculated were less than 5.0%, the solution methodology was verified.

3.2.2.4 Further observations

The solution developed in Chapter 2 was successfully implemented on the case study System A-1. The methodology identified the desired control strategy and the alternative implementation strategy to be used to achieve the desired results. No infrastructure changes and related capital costs were required. Energy savings were rendered and the solution verified.

Control parameters

Although not a part of the objectives, the control parameters had a significant impact on both the actual and theoretical values. Understanding how the control parameters changed provides further insight into any relevant changes made and the resulting energy improvements.

It is expected that the control parameters will either improve or be maintained close to their target values. In this case study, the control parameter was compressed air supply pressure. Targets were developed to guide the reduction of the supplied pressures. The average actual system supply pressure profile for 2019 is shown in Figure 3-18 along with the pressure baseline, goal target pressures, and adjusted target pressure profile.

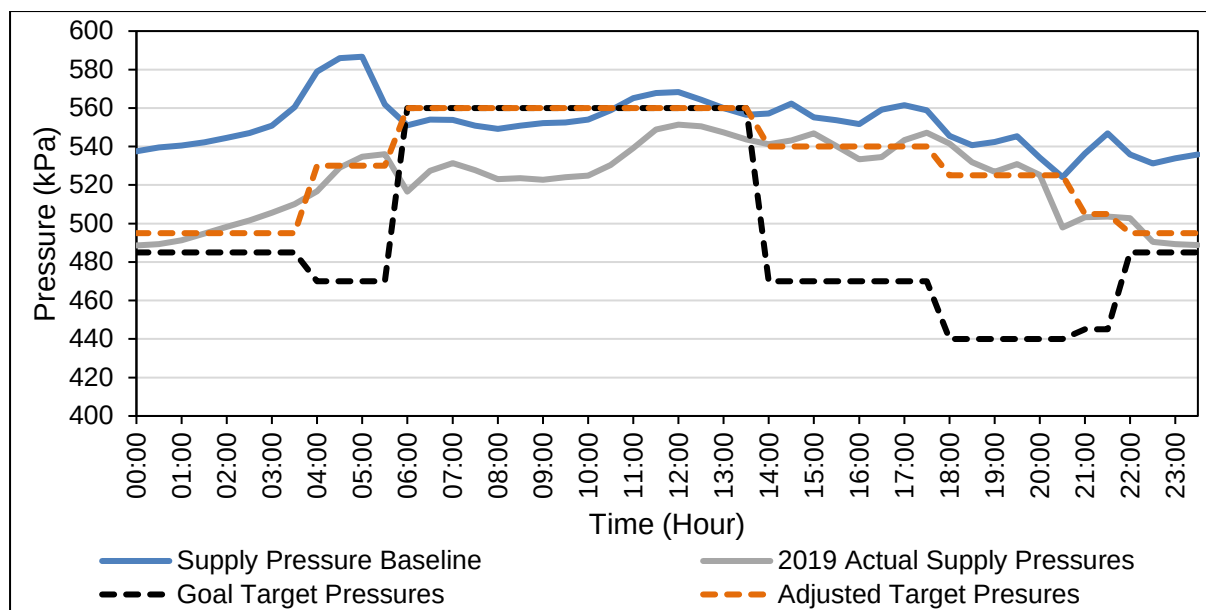


Figure 3-18: System A-1 2019 actual supply pressure comparison to baseline and target supply pressures

The difference between the 2019 actual pressure and the goal target pressures indicates the periods when implementation constraints were encountered. Pressures were greatly reduced during the night period between 22:00 and 04:00 when the Eskom TOU schedule indicates the low off-peak tariffs. Conversely, minimal pressure reductions occurred during the expensive standard and peak tariff periods. The greatest missed opportunity came in the afternoon period between 14:00 and 22:00 as pressures remained high.

The constraints experienced primarily consisted of additional work being carried out during afternoon periods and faulty demand-side machinery, both which required elevated pressures. These instances became far more frequent between November and January. Despite the difficulties, overall pressure reductions were observed. These observations further support the reasoning for the slight mismatch in the energy and cost saving deviations seen.

Furthermore, due to the difficulties experienced, the target pressures had to be adjusted at the end of Section 3.2.1.2 to align with the control that was implemented successfully. This produced more accurate theoretical energy improvement values for the verification process.

Due to the severe variability of the system pressures, the annual pressure trends were plotted as monthly averages. The calculation of these values excluded the peak drilling shift pressures as any pressure changes during the drilling period were not as a result of the implemented control. The trends for the 2018 and 2019 calendar year periods are shown in Figure 3-19.

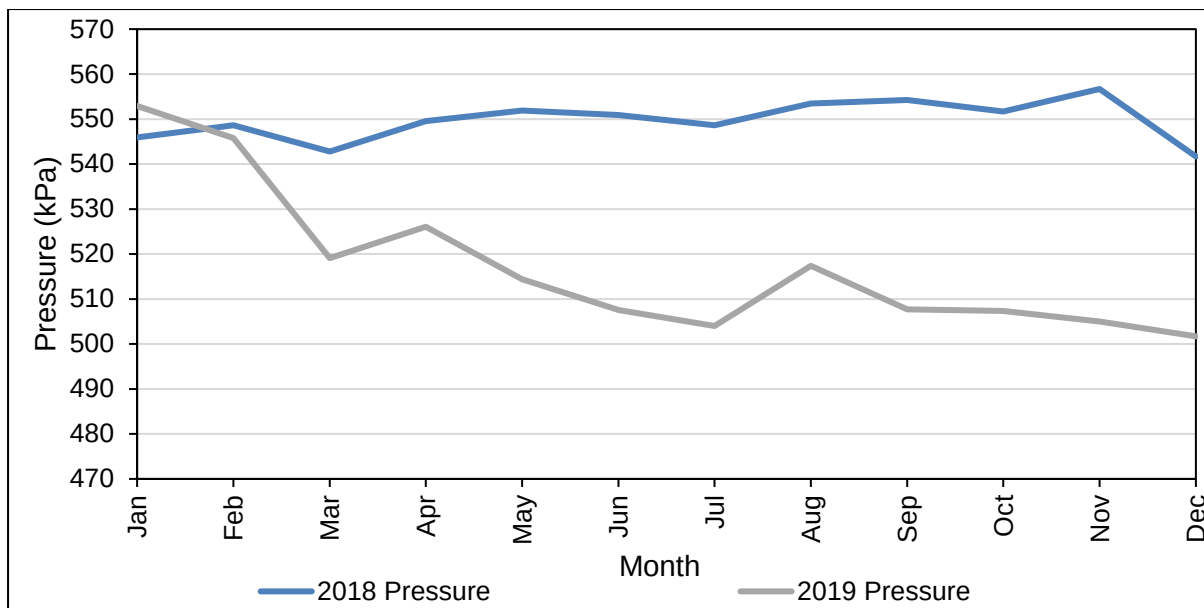


Figure 3-19: System A-1 monthly average supply pressure comparison between 2018 and 2019

The pressure reduction over the 2019 period is clearly shown in this figure, indicating improved pressure control. The initial pressure reduction in March 2019 occurred due to downtime caused by the permanent system changes made as well as maintenance on some shafts.

Energy and cost savings

The theoretical energy and cost savings were determined for the project and reported as the savings targets. While the energy savings targets had an error of only 0.8%, the cost savings deviated by 2.4% due to varying control implementation across the daily shifts. The cumulative daily energy saving and target trends for the implementation period are shown in Figure 3-20.

Notably, there were two instances in August 2019 and in February 2020, respectively, when incidents on the mine such as fires, machinery breakdowns, and additional operations caused severe decline in savings and even losses. As these instances were more significant than the average daily variations – each lasting roughly two weeks and beyond the control and scope of this study – the impacts thereof were simply separated and removed. Other occasional days also had to be filtered out due to incidents of a similar nature.

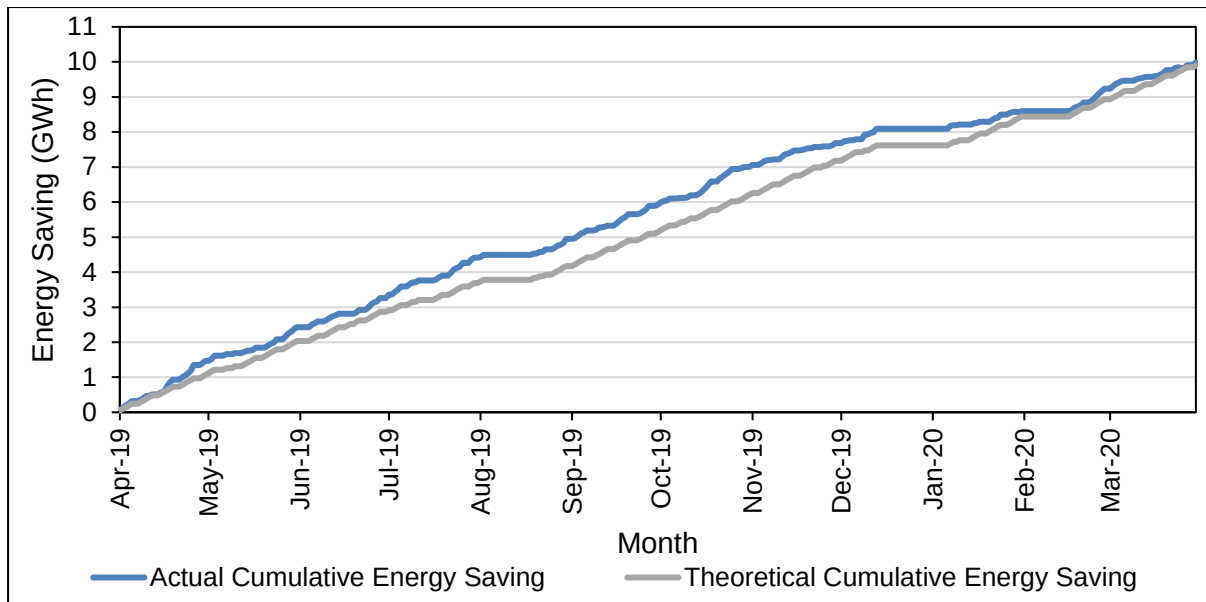


Figure 3-20: System A-1 2019–2020 cumulative actual and theoretical energy savings

The preceding figure shows the correlation between the two energy trends. The cumulative daily cost saving and target trends are shown in Figure 3-21.

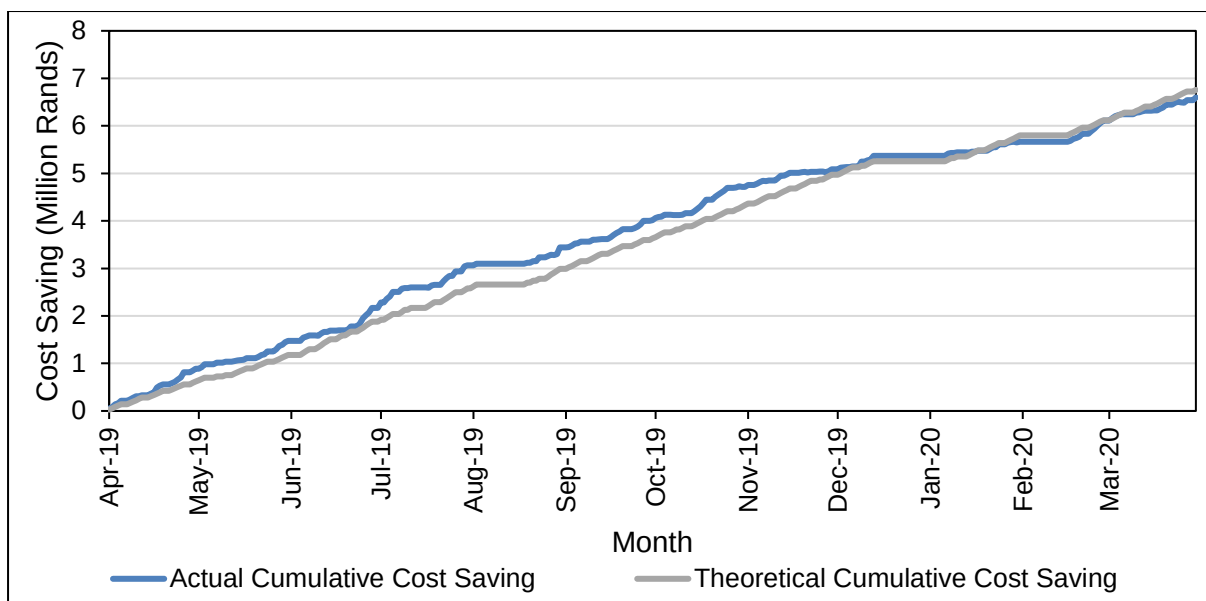


Figure 3-21: System A-1 2019–2020 cumulative actual and theoretical cost savings

On average the daily energy impact of the project was 44.4 MWh with an average power reduction of 1.8 MW over the day period. The theoretical model was verified as the solution produced energy and cost savings with an average error of less than 5.0%, rendering the implementation of the solution on case study System A-1 a success.

3.3 Case study – System B

In 2019, the developed solution from Chapter 2 was also implemented on case study System B. As done before, System B-1 denotes the configuration of System B shortly before the solution was first implemented early in 2019. Implementation on System B-1 only differed from that of System A-1 by the lack of a non-routine baseline adjustment. Therefore, the purpose of this case study is simply to provide secondary verification of the solution on a slightly simpler system to further support the validation process.

3.3.1 Implementation of solution

3.3.1.1 System analysis

At the beginning of 2019, the compressed air pipe network of System B-1 spanned 17 km. It connected eleven compressors from five compressor houses to four individual demands, all of which were active mineshafts. The analysis of the compressed air system as laid out in Section 2.2 was once again followed.

Compressed air system layout

The compressed air network, suppliers, and consumers were identified first and are shown in the satellite imagery in Figure 3-22. The compressed air network was a ring-feed system that fed its demands from six VK50 and five VK32 compressors as indicated in Figure 3-22 by the grey and black compressors, respectively. The average power and flow capacities of each of the compressors were the same as the VK50s and VK32s used on System A-1. System B-1 thus had a total installed power capacity of 43.3 MW.

An additional sixteen small L250 compressors were commissioned on the system early in 2019. They were located adjacent to Shaft 4B, each with a capacity of 0.25 MW. However, the use of these smaller compressors during 2019 was limited due to incorrectly sized pipelines installed to connect these compressors to the network. The smaller pipelines only allowed for six of the sixteen compressors to operate without resulting in a significant pressure drop over the pipeline. Due to the limitations, the six L250 compressors were only operational on weekdays between 08:00 and 12:00 and no changes were permitted. Therefore, these compressors were not considered to be part of the control strategy implemented in this study. However, the six additional L250s did increase the operational installed capacity to 44.8 MW.

As both System A and System B belonged to the same mining group and shared some systems such as the SCADA, it was not surprising to find that System B-1 also had little to no

automated control on the compressors or at the demands. Compressors were being manually started and stopped to maintain pressures that were far above the demand-side requirements.

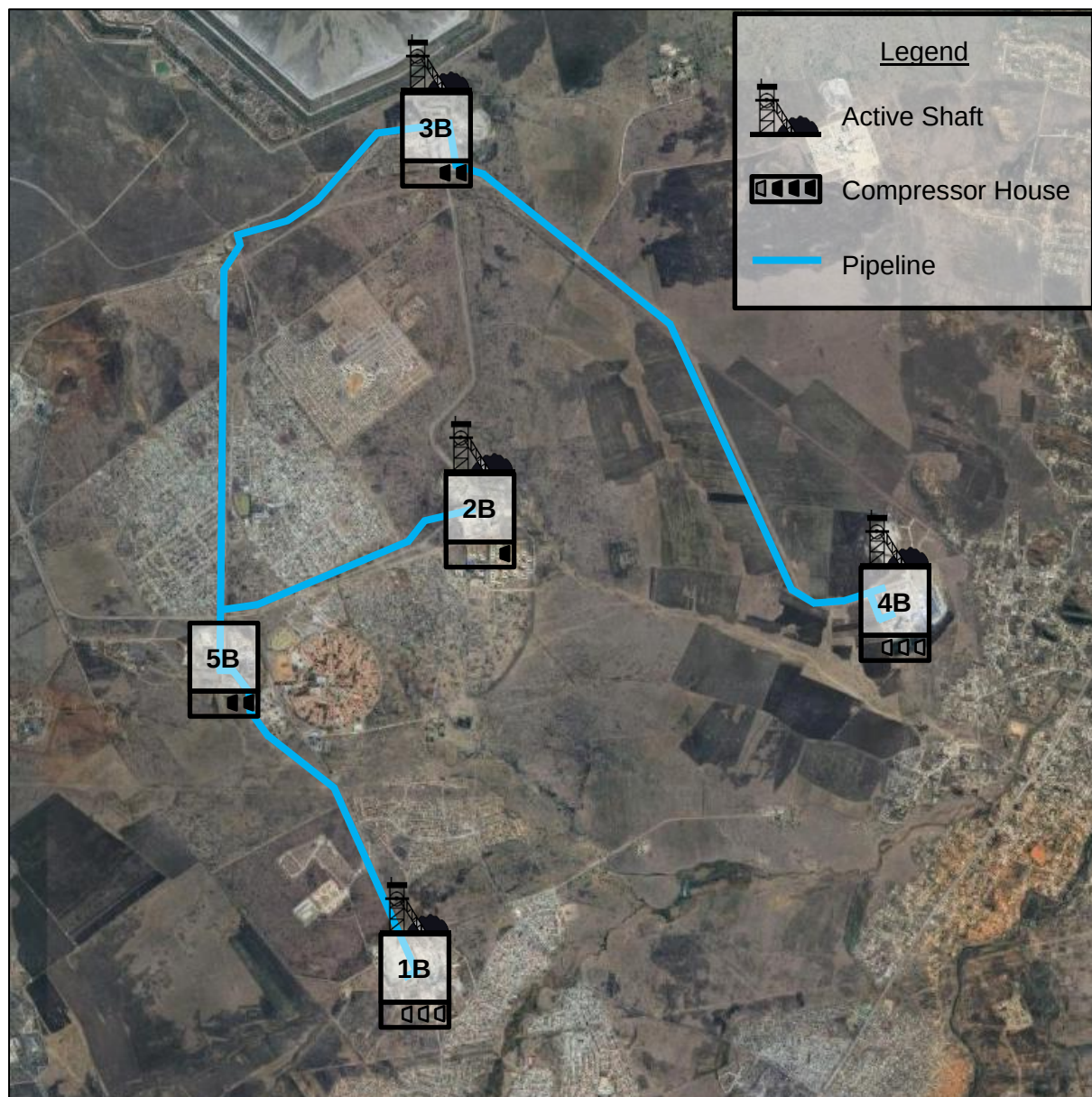


Figure 3-22: System B satellite image

The individual efficiencies of the compressors unfortunately could not be calculated accurately due to insufficient, unreliable data. The locations of the various compressors are summarised in Table 3-14. The consumers on the system were identified and their locations are also provided in Figure 3-22. None of the consumers had any kind of control valve installed and thus could not implement valve control. The demands are summarised in Table 3-14.

Table 3-14: System B-1 demands and suppliers

Facilities	Demands	Suppliers	Compressors
1B	Shaft 1B	Compressor House 1B	3 × VK50
2B	Shaft 2B	Compressor House 2B	1 × VK32
3B	Shaft 3B	Compressor House 3B	2 × VK32
4B	Shaft 4B	Compressor House 4B	3 × VK50
5B	–	Compressor House 5B	2 × VK32

As the system layout was known, the system operation could be investigated further.

Operational schedules

As System B operated under the same mining group and in the same general geographical area as System A, System B-1 used the same exact shifts as System A-1 as shown in Table 3-2. The schedule is also shown in Figure 3-23 along with a typical total power profile for the System B-1 compressors.

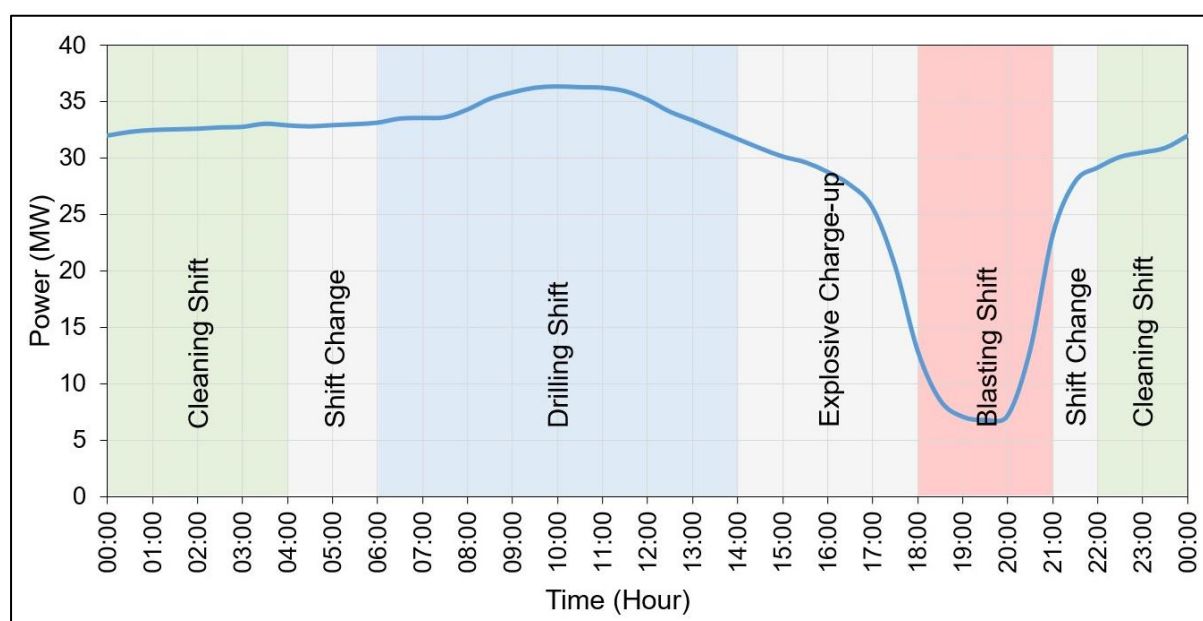


Figure 3-23: System B-1 typical compressors power demand profile and schedule

The profile reached its peak during the drilling shift when the most compressors were operational. During the drilling shift, the system operated at 94.4% of its full operational capacity on average with the total capacity of reserve compressors close to 3 MW. The

reserve compressor selection could use one of a few possible arrangements depending on the specific demand conditions at the time. This left room for demand expansion in the peak drilling period as demand-side operations continued to grow. The lowest point on the profile occurred during the blasting shift when the fewest compressors were in use. Often during the blasting shift, only one VK32 compressor was used as the standard arrangement. This compressor ensured that the essential systems at the shafts received adequate compressed air supply.

3.3.1.2 Operational requirements

According to the methodology developed in Section 2.3, the strategies that can be implemented fully must be determined first, followed by those to be considered for principle-based implementation.

Determine implementation strategies

The strategies that could be implemented fully on System B-1 were identified, and the outcome of the investigation is summarised in Table 3-15. This table was developed based on Table 2-4.

Table 3-15: System B-1 strategies full implementation checks

Strategies	Infrastructure	Data	Completeness	Incomplete items
Valve control	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves
Guide vane control	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Systems out of date, need repair
Compressor schedules	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Insufficient and unreliable data
Automation of compressed air control	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, functional systems, and required data

The investigation rendered a null result as no strategies could be implemented fully and the first strategy, namely valve control, could not be implemented for the reasons shown in Table 3-16.

Table 3-16: System B-1 valve control full implementation checks

Consumers	Infrastructure	Data	Incomplete items
1B	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
2B	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
3B	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data
4B	☐ Complete ☒ Incomplete	☐ Complete ☒ Incomplete	Lack of control valves, measurement instrumentation and data

As no strategies could be implemented fully, a further investigation was carried out to identify which alternative strategies were possible for principle-based implementation of valve control. The outcome of the investigation is summarised in Table 3-17.

Table 3-17: System B-1 valve control principle-based implementation checks

Strategies	Infrastructure	Data	Implementation
Valve control	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete

The earlier investigation carried out to identify strategies for full implementation eliminated all the automated control based strategies and it only left manual network control to be investigated. The investigation produced a positive result, indicating that manual network control was possible. The complete and summarised results of the investigations are listed in the elimination rubric of Table 3-18. This table was developed based on Table 2-6.

Table 3-18: System B-1 strategies elimination rubric

Strategies	Full	Principle	Implementation	Principle strategy
Valve control	☐ Complete ☒ Incomplete	☒ Complete ☐ Incomplete ☐ N/A	☐ Full ☒ Principle ☐ None	☒ MNC complete ☐ GVC complete ☐ CS complete ☐ ACC complete ☐ All incomplete ☐ N/A
Guide vane control	☐ Complete ☒ Incomplete	☐ Complete ☐ Incomplete ☒ N/A	☐ Full ☐ Principle ☒ None	☐ MNC complete ☐ CS complete ☐ All incomplete ☒ N/A
Compressor schedules	☐ Complete ☒ Incomplete	☐ Complete ☐ Incomplete ☒ N/A	☐ Full ☐ Principle ☒ None	☐ MNC complete ☐ All incomplete ☒ N/A
Automation of compressed air control	☐ Complete ☒ Incomplete	N/A	☐ Full ☒ None	N/A

The focus could then shift to determining the control targets as the strategy was clear.

Determine control targets

For the implementation of manual network control, surface pressure targets had to be determined for the system. The same historical data analysis process used for System A-1 was used to produce the relevant profiles for System B-1. The set of frequency plots for the average demand pressures for the whole of System B-1 are shown in Figure 3-24 for each shift from Table 3-2.

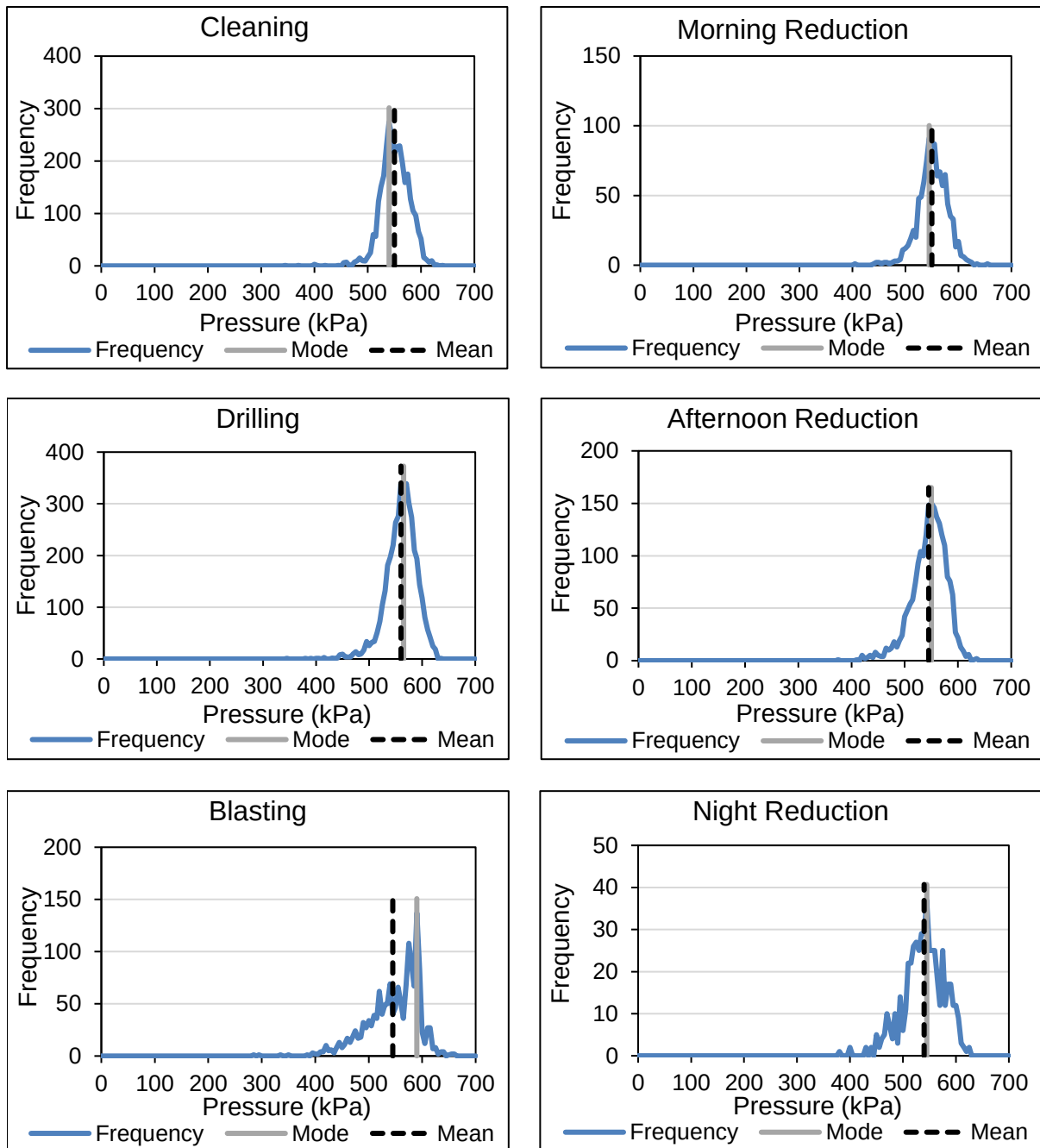


Figure 3-24: System B-1 pressure distribution per shift

The mode values experienced the same issues here as with System A. Therefore, as the mean values were more stable and representative of the normal demand pressures, they were used to develop the initial pressure target profiles. The average full-day pressure profile for System B-1 along with the profiles developed by the mean and mode pressure values are shown in Figure 3-25.

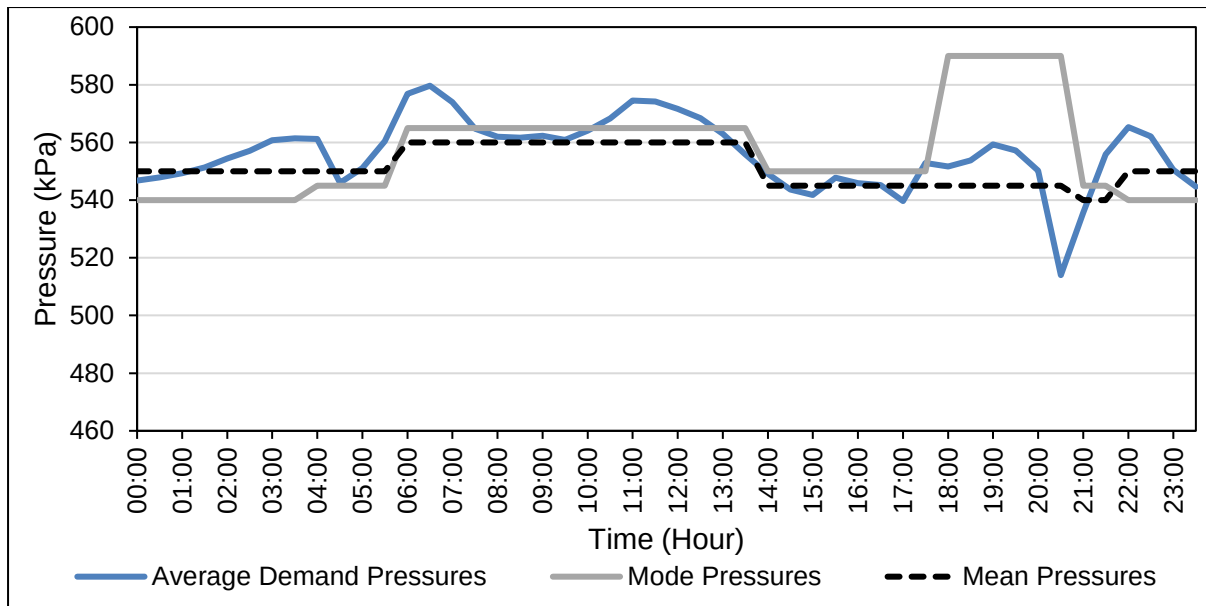


Figure 3-25: System B-1 demand pressure profiles

The mean frequency pressures for each period are summarised in Table 3-19 and represent the starting pressure targets for the individual consumers in kilopascal.

Table 3-19: Starting pressure targets for each demand on System B-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
1B	575	570	585	555	555	555
2B	555	550	560	540	540	535
3B	530	535	540	540	545	525
4B	545	555	560	545	550	540

The various equipment used at the shafts during each shift was the same as that of System A-1 and the corresponding pressure requirements were already summarised in Table 3-8. The resulting maximum pressure requirements for each shift were thus also the same and are summarised in Table 3-9.

The System B-1 starting pressure targets (Table 3-19) were adjusted to be equal to the shaft pressure requirements only where the starting pressure targets were greater than the pressure requirements. Due to the high average starting pressures, this was the case for all shafts during all periods. The adjusted starting pressure targets are provided in kilopascal in Table 3-20.

Table 3-20: Adjusted starting pressure targets for each demand on System B-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
1B	500	485	510	485	475	485
2B	500	485	510	485	475	485
3B	500	485	510	485	475	485
4B	500	485	510	485	475	485

The demand-side engineers were consulted who adapted the goal pressure targets according to the particular requirements of their respective shafts. The adapted pressure targets are shown in Table 3-21 in kilopascal and form the goal pressure targets of the system.

Table 3-21: Goal pressure targets for each demand on System B-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
1B	500	470	600	470	440	445
2B	485	470	590	470	440	445
3B	515	470	560	470	440	445
4B	500	470	580	470	440	445

The expected pressure reductions outside the drilling shift become evident when the 2018 baseline supply pressures and the goal pressure targets are compared in Figure 3-26. These pressure targets were used for implementation. However, it is later shown in Section 3.3.2.4 that significant constraints were encountered that caused the control targets to be elevated. As stipulated in Section 2.5.3, in order to supply accurate theoretical energy improvement values, the pressure targets had to be adjusted at all times outside the drilling period. The adjusted targets are shown in Table 3-22.

Table 3-22: Adjusted pressure targets for each demand on System B-1

Consumers	Cleaning shift	Morning reduction	Drilling shift	Afternoon reduction	Blasting shift	Night reduction
1B	535	540	600	545	540	510
2B	520	520	590	530	535	495
3B	500	505	560	525	535	490
4B	525	535	580	540	550	520

Figure 3-26 includes the adjusted pressure targets for System B-1.

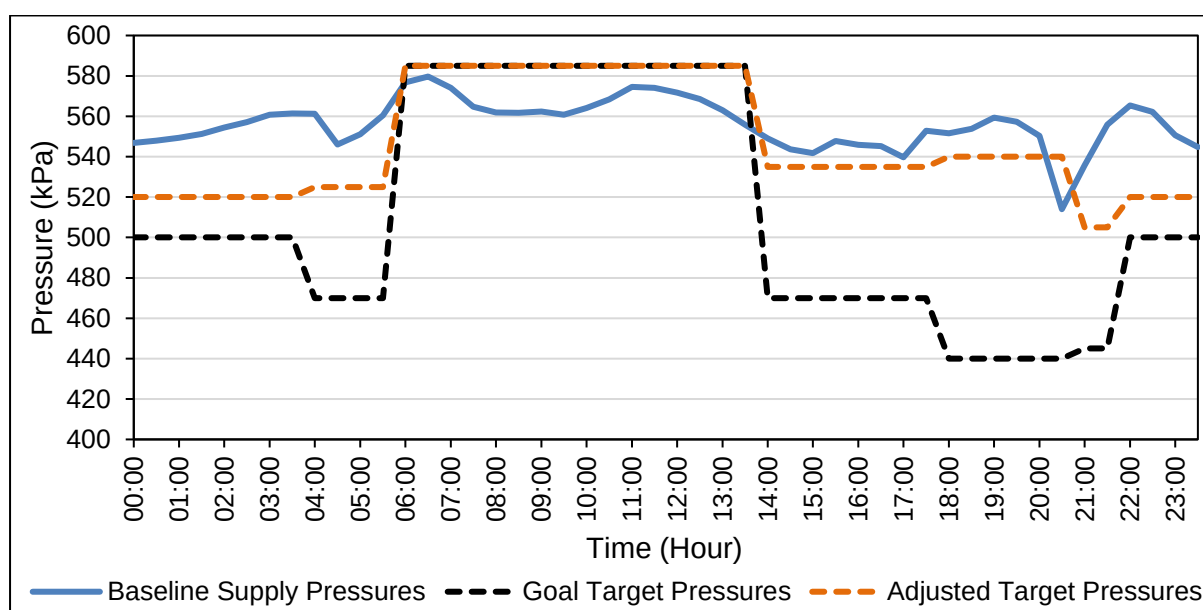


Figure 3-26: System B-1 initial supply and target pressure profiles

The adjusted targets are referred to as the theoretical pressures or simply the target pressures from this point forward.

3.3.1.3 Implementation

The requirements and implementation of control were first considered, followed by monitoring as stipulated in Section 2.4.

Control

As the only strategy being implemented was manual network control, the only control required was stopping and starting compressors to meet pressure requirements. The implementation of control is primarily dependent on the system software and the mine's IT policies. Systems

A and B shared most of the same software, so again the only control software available at the time was a SCADA (Figure 3-6), and IT policies prohibited changes to the programming thereof.

The control room operators could view the System B-1 pressures, available compressors, and all parameters needed for the control. The surface pressure and demand flow were both indicated for each demand. The available compressors for each compressor house as well as their statuses were shown as previously summarised in Table 3-13. Manual network control could, therefore, be implemented due to the availability of these systems.

Monitoring

For this solution, the control parameters needed to be monitored to ensure the pressures were maintained close to the targets. Again, ideally the pressure targets were to be programmed into the SCADA system, which the mine's IT policies did not allow. Therefore, the implementation strategy for the required monitoring focused on the same simple external system as used on System A-1. The developed Excel dashboard used for monitoring of the control parameters was shown in Figure 3-7.

3.3.2 Results

3.3.2.1 Development of baselines and theoretical values

The necessary baselines and scaling and adjustment methods used in determining the solution savings were developed according to the methods discussed in Section 2.5.

Baseline development

The power baseline was developed for weekdays from the year 2018, prior to the implementation of the developed solution in 2019. Any data in 2018 that came after 24 August 2018 was excluded from the baseline period as a temporary system change had occurred from that date. The system change was an underground connection between Shafts 1B and 4B to improve underground pressures between the shafts. This change caused elevated demands and would skew any baselines should this change be included in the process.

Since the underground pressures showed no improvement, the underground connection was severed by 8 April 2019. This came after an unrelated incident had occurred at Shaft 4B on 1 March 2019, followed by another incident at Shaft 1B on 8 April 2019. These incidents caused Shaft 4B to close between 1 March 2019 and 15 March 2019, and Shaft 1B to close between 8 April 2019 and 22 May 2019 – each pending an investigation regarding the

incidents. These downtime periods not only caused reduced demands but also provided the opportunity to close the connection between the shafts.

The developed power baseline was adjusted daily according to the peak drilling period consumption as stipulated by the baseline methods. Furthermore, the pressure, flow, KPI, and specific power baselines from 2018 had to be determined in a similar fashion but did not undergo any form of routine scaling.

Non-routine baseline adjustments

Unlike System A-1, the compressor supply network on System B-1 was not running at full capacity during the peak drilling period in 2018. Along with the fact that no permanent system changes were made, it was therefore not necessary for any non-routine baseline adjustments in 2019. As no non-routine baseline adjustments were used, the power baseline and actual power values could be used as they were, and only routine baseline adjustments were made.

Calculation of theoretical values

The theoretical potential savings first had to be determined to motivate implementation and verify the solution. There is no payback period as this study only sought to implement projects that required no capital investment.

To calculate the potential energy and cost savings for the study, the projected 2019 KPI profile was determined. This is done to consider the average year-on-year expected base KPI increase due to system expansion and further leak and inefficiency growth on the demand-side. The 2018 daily average base KPI trend excluding the December break periods is shown in Figure 3-27. The linear trend was developed from this data, which showed a 25.5% increase over the period. However, when any data after the temporary system change was implemented on 24 August 2018 is excluded, the extrapolated linear adjusted trend tends to an average increase of 10.0% for the same period.

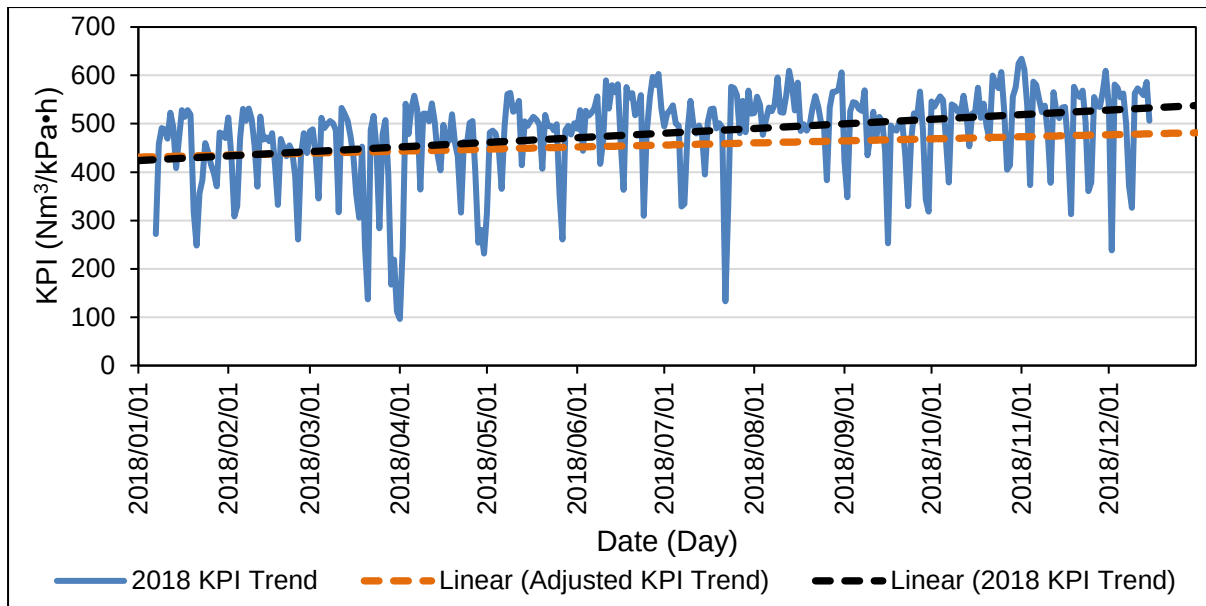


Figure 3-27: System B-1 2018 demand KPI trend

It was assumed that the system base KPI would follow a similar upward trend of 10% in 2019 over the year period. The projected KPI profile was calculated by inserting the KPI baseline and $c_I = 10\%$ into Equation 2-4. This was followed by calculating the theoretical specific power for 2019 using Equation 2-7, and the projected and theoretical flows using Equation 2-5. These profiles are available in Appendix A. Finally, the corresponding power profiles along with the supply- and demand-side theoretical power savings were determined by means of Equation 2-8.

Both the 2019 projected power and theoretical power profiles are shown in Figure 3-28 along with the individual contributing supply- and demand-side power savings. The data for the projected and theoretical profiles is available in tabular form in Appendix B.

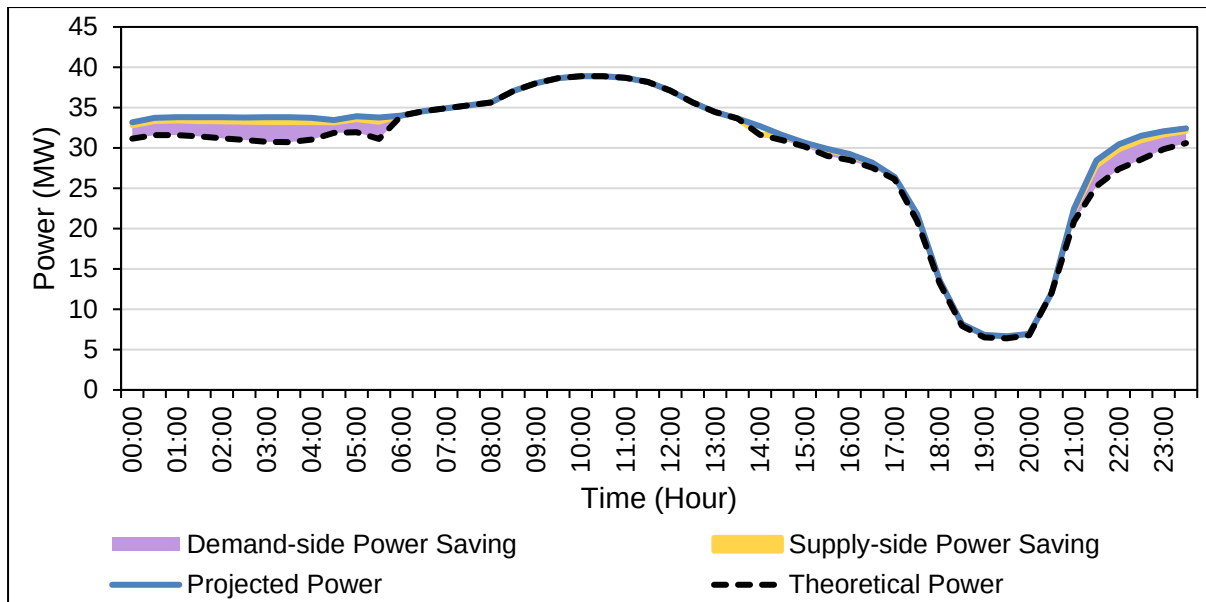


Figure 3-28: System B-1 projected and theoretical power profiles

The theoretical savings were calculated and produced expected annual energy and cost savings of 4.7 GWh and R3.3 million, respectively, at 2018–2019 Eskom rates (R4.5 million – 2022 Eskom rates). The total theoretical saving was divided between the contributors, the supply- and demand-side by 19.8% and 80.2%, respectively.

3.3.2.2 Calculation of energy improvement

As shown in Figure 3-29, the actual daily energy and cost savings were calculated with the difference between the scaled baseline and actual power profiles.

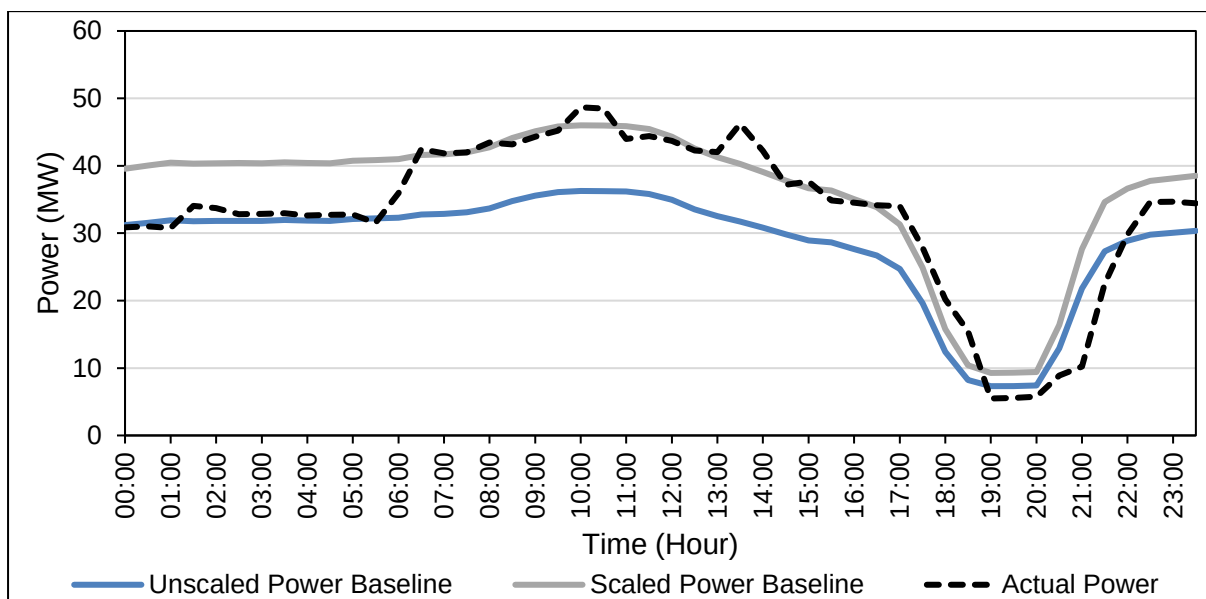


Figure 3-29: System B-1 power baseline scaling example

The energy and cost savings were recorded from the start of the project in April 2019. By the end of December 2019, the project had accumulated 3.6 GWh and R2.7 million (R3.7 million – 2022 Eskom rates) in energy and cost savings. The savings were further recorded until the end of March 2020 when cumulative savings of 4.6 GWh and R3.4 million (R4.7 million – 2022 Eskom rates) had been realised.

3.3.2.3 Verification of solution

The accuracy of the developed solution was verified using Equation 2-11. The theoretical annual energy savings provided at the end of Section 3.3.2.1 exceeded the actual savings by 3.2%, while the annual cost savings target fell short by 4.1%. As the theoretical energy savings had overestimated while the theoretical cost savings underestimated the actuals, this indicated that some energy savings realised during high-tariff periods exceeded expectation, while energy savings realised during low-tariff periods were less than expected. Nevertheless, the solution methodology was verified as the error values calculated were less than 5%.

3.3.2.4 Further observations

The solution developed in Chapter 2 was implemented on case study System B-1. The methodology identified the desired control strategy and the alternative implementation strategy to be used to achieve the desired results. No infrastructure changes and related capital costs were required. Energy savings were rendered and the solution was verified.

Control parameters

It is expected that the control parameters will either improve or be maintained close to their target values. The average system pressure profile for 2019 is shown in Figure 3-30 along with the pressure baseline, goal target pressure profile, and adjusted target pressures. The difference between the 2019 actual pressure and the goal target pressures indicates the periods when constraints were encountered during implementation. Pressures were greatly reduced during the night period with low off-peak Eskom tariffs. Meanwhile, pressure reductions during the more expensive Eskom tariff periods were minimal, with the greatest missed opportunity in the afternoon period. However, the pressure reductions between 20:30 and 21:30 were above expectation. As this fell in a more expensive period, it increased the actual cost savings above the theoretical savings.

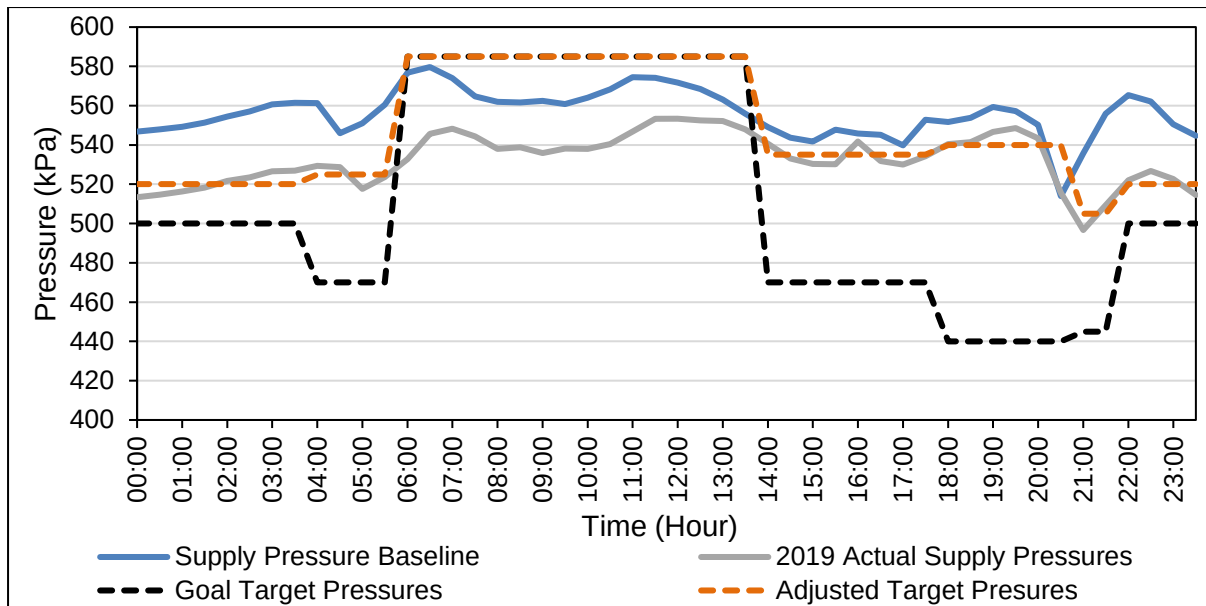


Figure 3-30: System B-1 2019 actual supply pressure comparison to baseline and target supply pressures

The constraints experienced were very similar to those of System A-1. Primarily, the constraints were due to extensive additional work during afternoon periods, faulty machinery, and several incidents on the shafts of varying severity. The frequency of these instances increased from November to January, which is to be expected due to the relation of operations of Systems A and B. Despite the hindrances, pressure reductions were observed. However, these difficulties did result in adjustments to the pressure targets.

The monthly average 2018 and 2019 pressure trends, excluding peak drilling shift pressures for the system, are shown in Figure 3-31. The pressure reduction over the 2019 period when compared with 2018 is evident in the figure. The reduced pressures during the period from January to March 2019 were caused by the temporary connection between 1B and 4B shafts, as well as the incidents that occurred at these shafts.

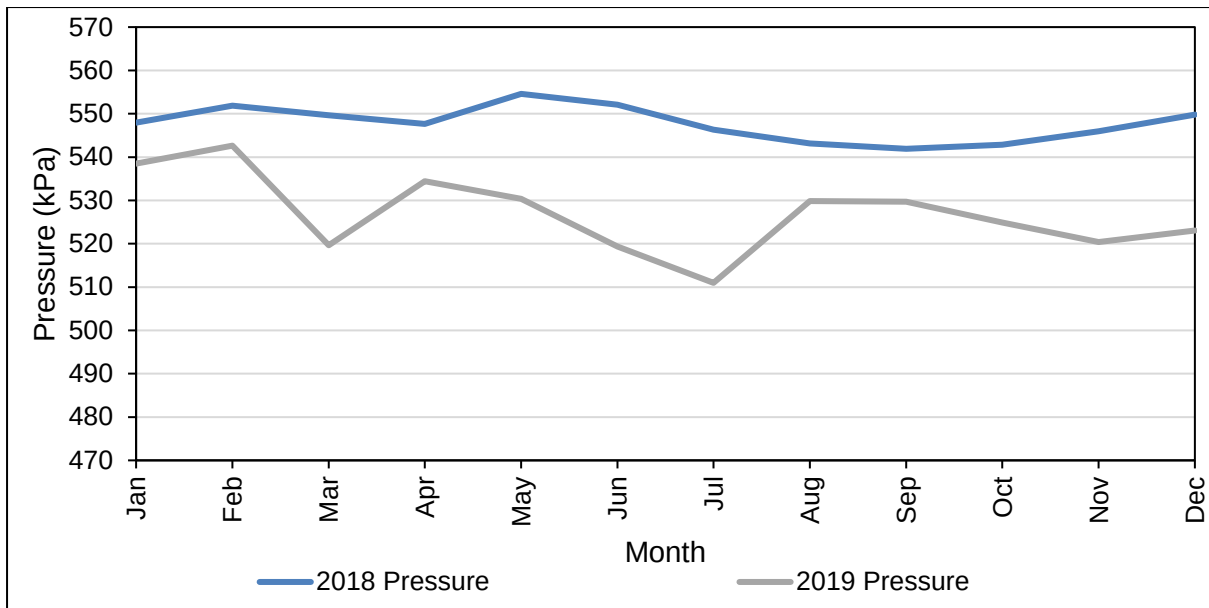


Figure 3-31: System B-1 monthly average supply pressure comparison between 2018 and 2019

The observed pressure trends and profiles indicate that the target pressures had to be adjusted to align with the control that was implemented. More accurate theoretical energy improvement values were thus calculated for the verification process.

Energy and cost savings

Expected energy and cost savings were determined for the project and reported as the savings targets. The energy savings target error was 3.2% and the cost savings target was 4.1%. The cumulative energy savings and target trends are shown in Figure 3-32.

There were a multitude of incidents that resulted in losses. Some incidents, such as those at Shaft 1B from 8 April 2019, were far more pronounced than others due to the duration thereof. Other significant incidents that were also out of the control and scope of this study occurred frequently on System B-1 and had to be filtered out to provide an accurate account of the savings achieved by the implemented solution. This did not include the smaller daily variations as the routine baseline scaling was expected to account for the majority thereof.

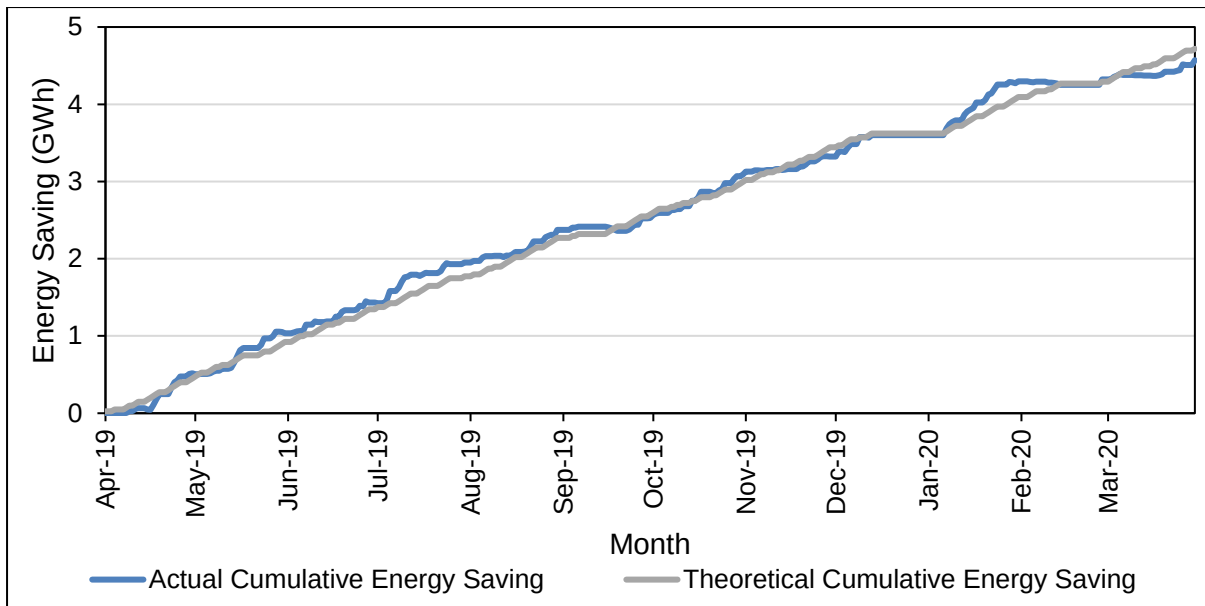


Figure 3-32: System B-1 2019-2020 cumulative actual and theoretical energy savings

The cumulative cost savings and target trends are shown in Figure 3-33.

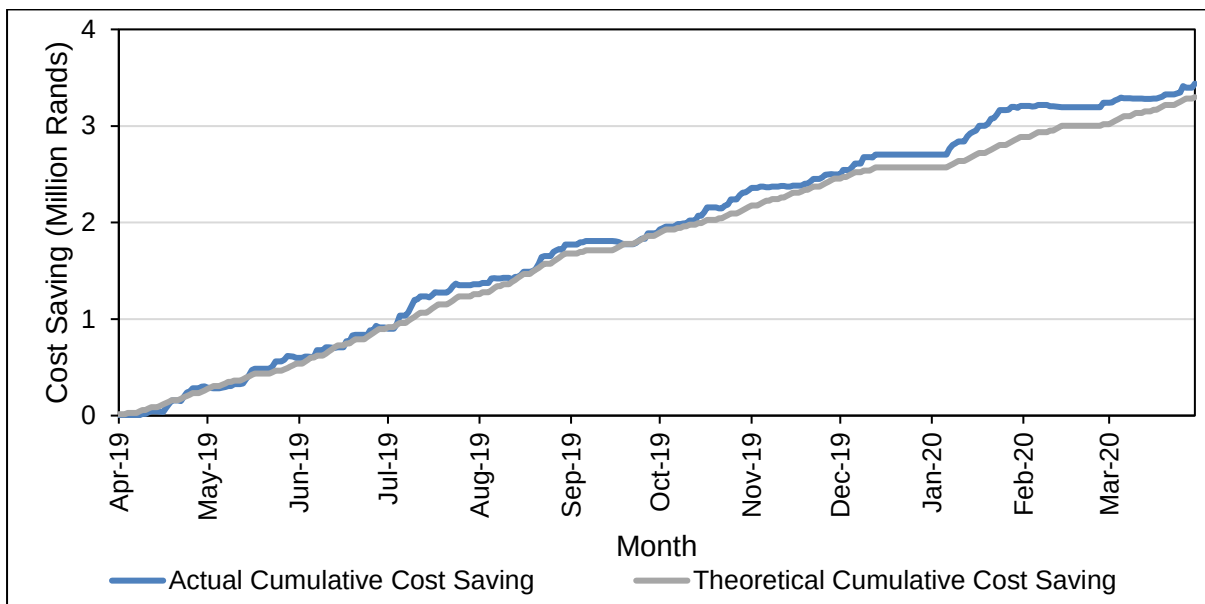


Figure 3-33: System B-1 2019-2020 cumulative actual and theoretical cost savings

On average, the daily impact of the project had energy savings of 18.9 MWh with an average power reduction of 0.8 MW over a day period. The solution produced energy and cost savings with an average error of less than 5% as expected on case study System B-1, thus verifying the theoretical model.

3.4 Discussion, validation, and valuation of results

3.4.1 Discussion of results

The methodology developed in Chapter 2 was applied to the two case study systems. Of the two systems, System A was the larger and System B the smaller. In 2019, the solution was implemented on both case study systems in which no automated control strategies could be implemented fully. However, valve control could undergo principle-based implementation via manual network control. The implementation of the solution rendered energy and cost savings of 10.0 GWh and R6.6 million (R9.0 million – 2022 Eskom rates) on System A, and 4.6 GWh and R3.4 million (R4.7 million – 2022 Eskom rates) on System B.

Following implementation on case study System A-1, the theoretical energy savings had an error of only 0.8% while the cost savings deviated by 2.4%. On System B-1, the theoretical energy savings error was 3.2% and the theoretical cost savings was 4.1%. In both cases, the deviations occurred due to varying control implementation across the daily shifts. There were two primary reasons for the variations on both systems. The first was human error as the control was a manual process that control room operators were tasked with and thus the control adjustments were incomplete or delayed in their implementation. Secondly, the theoretical model was developed to assume normal operations and demands. Frequent deviations occurred in reality.

From Section 1.3 it was observed from literature that studies that had fully implemented valve control achieved average daily energy savings in the range of 0.3% to 1.8% of their system capacities. The implementation of the solution on System A-1 and System B-1 did not allow for full implementation but principle-based implementation of valve control via manual network control. This resulted in average daily energy savings of 2.9% and 1.9% of their system capacities for Systems A and B, respectively. As the energy savings produced by the developed solution exceeds those from literature, it is concluded that the implementation of a desired strategy using an appropriately selected alternative strategy that uses the same primary control principle is possible and effective.

3.4.2 Validation of results

The developed solution methodology was used successfully to identify, implement, and evaluate control strategies. The solution worked within system limitations, resulting in no direct changes to the system infrastructure and thus avoiding the associated capital cost involved. The solution also produced theoretical and actual energy savings that verified the solution

when it was implemented on the individual case studies. The developed solution is therefore validated as the results addressed the problem statement and satisfied the study objectives.

3.4.3 Value to industry

South Africa has 26 active platinum mines and is responsible for between 75% and 80% of the world's platinum group metal production [60]. The 26 mines are all found in the Bushveld Igneous Complex as shown in the satellite imagery in Figure 3-34.

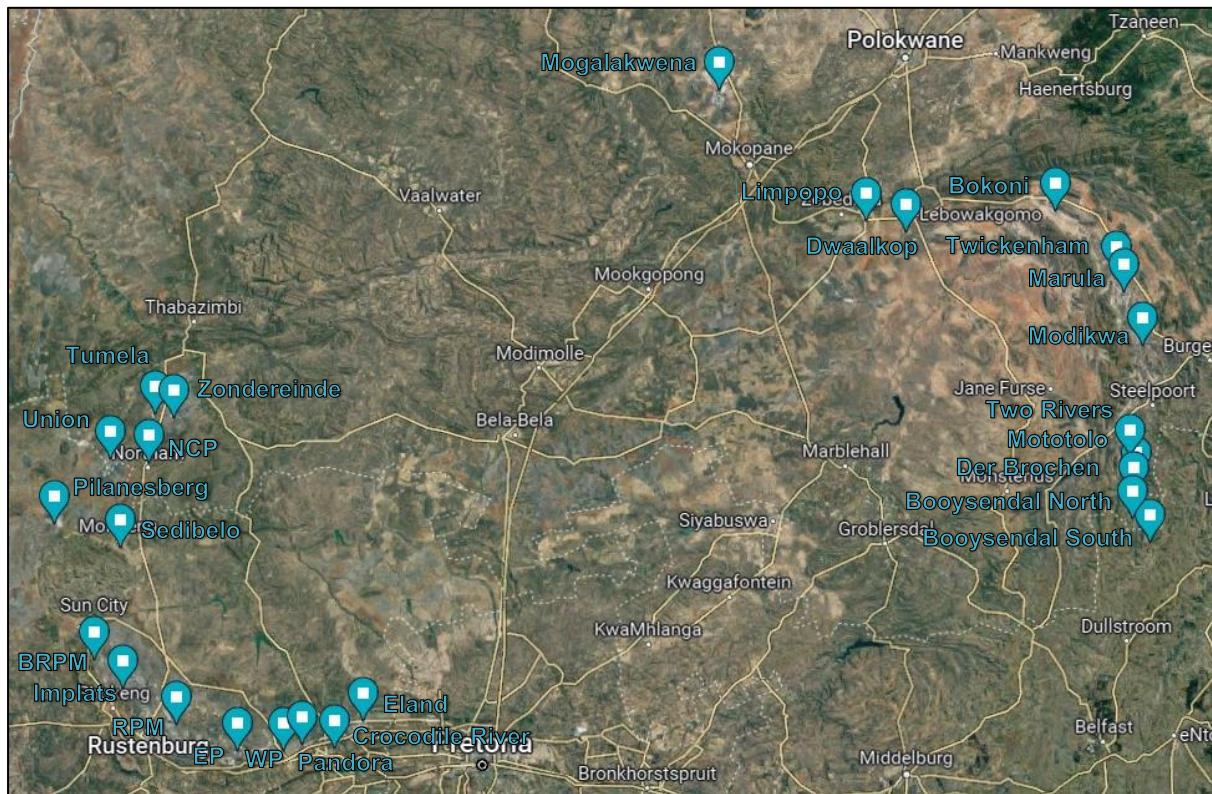


Figure 3-34: Platinum mines of South Africa (adapted from [60])

The possible impact that the developed solution could have on the South African platinum mining industry can be approximated under the following assumptions:

- Each mine is only capable of achieving 50% of the total potential savings as rendered in this study as it is not expected that these systems would have the exceptional lack of infrastructure as seen on the case studies considered.
- The capacity of each mine compressed air system is only 75% of the combined capacity of the two case study systems from the large mining group used in this study.

The combined annual savings of the case studies herein equate to R13.4 million per annum at 2022 Eskom rates. Considering the listed assumptions, the South African platinum industry alone has potential savings of R130.7 million per annum.

The developed solution could also have an impact on the South African gold mining industry. However, the gold mining sector in South Africa is not what it used to be as its glory days began to fade in the early twenty-first century around the global financial crisis of 2008 [61]. Nonetheless, there are still 41 active underground gold mines in the country that are now responsible for less than 4.2% of total global production [61]. Gold mining is significantly more spread out across parts of the country than platinum mining, which makes it challenging to capture in sufficient detail with satellite imagery.

Due to operational differences from platinum mining, approximating the impact the developed solution could have on the gold mining sector would differ to some extent. Hypothetically, should the same assumptions be made, the gold mining sector would have a further R206.0 million in potential savings annually. Thus, the South African underground mining industry would have total potential savings of R336.7 million per annum with the advent of the developed solution.

3.5 Summary

The methodology developed in Chapter 2 was applied in Chapter 3 to two case study compressed air networks, namely Systems A and B, from the same deep-level platinum mining group in the North West province of South Africa. System A is the larger of the two systems and System B the smaller, each spanning 38 km and 17 km, respectively.

On both System A-1 and System B-1, the only feasible strategy for implementation was manual network control as a substitute strategy for automated valve control as they shared the same core control principle. Implementation rendered actual annual cost savings of R9.0 million and R4.7 million for systems A and B, respectively, at 2022 Eskom rates. The theoretical savings calculated deviated from the actuals by less than 5% for both systems and the solution was thus verified.

Hereafter, a critical discussion of the study results highlights any observations around the significant values. The results were validated by confirming the study problem statement and objectives being satisfied. Finally, by extrapolating the savings obtained, the potential benefit across the South African mining industry was calculated to be approximately R336.7 million per annum at 2022 Eskom rates.

CHAPTER 4: CONCLUSION

4.1 Preamble

Chapter 4 provides a synopsis of the study that discusses the details of each chapter and further substantiates the fulfilment of the study objectives. The limitations experienced are addressed and recommendations for future work are made. Finally, the study closure is provided.

4.2 Summary of study

The cost of electricity remains one of the leading factors the mining industry faces regarding overinflated operating costs. Of these costs, at least 20% can be attributed to compressed air systems, indicating that the implementation of energy efficient procedures in this area could be of great benefit.

The need for a potential solution was identified that encompassed the core principles of previous automated strategies used for energy-saving solutions, while also avoiding the need for costly upgrades to software and instrumentation that would delay implementation and affect potential savings.

The main objective of this study was developing a methodology to produce energy savings on systems with limited infrastructure based on the fundamental principles behind popular automated compressed air control strategies. This was done by addressing the following study objectives:

- Develop a methodology used to identify, implement, and evaluate control strategies with the purpose of:
 - Avoiding directly effecting any change to the existing infrastructure, thus avoiding the associated capital cost thereof; and
 - Yielding energy savings.
- Implement and verify the developed methodology.

To provide a solution to the problem statement, Chapter 2 outlined the process to develop the solution methodology. The four-part methodology utilised automated control principles in its implementation of a cost saving strategy on a mine compressed air network, while taking the limitations of existing mine infrastructure into account.

A method was developed and used to identify possible control strategies for full or principle-based implementation. Thereafter, a method was developed which determined the theoretical energy improvement of a proposed control strategy. The latter had the purpose of analysing and motivating whether the solution would be effective. If multiple strategies were identified by the first method, the aforementioned method would identify the most effective option of the possible solutions. These methods functioned within the existing system limitations.

The first part of the methodology consisted of a system analysis that provided details on how to investigate the existing network layout, capacities and locations of the available suppliers, consumers and operational schedules used. This was followed by generating a detailed breakdown of the limited infrastructure, systems, data and software critical to the variety of common strategies.

Second was the evaluation of operational requirements that were determined by first identifying the different strategies and their respective counterparts to be used in the event of principle-based implementation thereof. After the strategy identification method was developed, the process of determining the control parameter targets was laid out.

Third, an implementation strategy was developed by focusing first and foremost on the control requirements and the systems and tools available to enable said control. The same was done in regard to monitoring and identifying the requirements and the implementation.

The last part of the method was to detail the verification process, which started with baseline development and guidelines based on critical topics highlighted by the IPMVP. The evaluation method was developed during which some of the points raised in the baseline development guidelines were addressed and the techniques used to perform baseline adjustments introduced. How the actual energy improvement is calculated was presented. The process used to verify the theoretical model and the solution accuracy was shown, which highlighted the importance of accounting for influential system changes.

The methodology developed in Chapter 2 was applied to Systems A and B, two case study compressed air networks. These networks were located in the same deep-level platinum mining group in the North West province of South Africa. The sizes of the systems were 38 km across for System A and 17 km across for System B.

The only implementation strategy that was feasible for Systems A-1 and B-1 was a manual network control that was used as a substitute for automated valve control. After implementation, annual savings based on 2022 Eskom rates were as follows: R9.0 million for System A and R4.7 million for System B. The theoretical savings calculated deviated from the

actuals by less than 5% for both systems and the solution was thus verified. No payback period was applicable as no capital was invested into infrastructure.

A critical discussion of the study results followed which highlighted observations around significant results and values. The results were validated by confirming the study problem statement and the objectives being satisfied. Finally, the potential benefit across the South African mining industry was calculated by extrapolating the savings obtained. The potential benefit was calculated as approximately R336.7 million per annum at 2022 Eskom rates.

4.3 Limitations and recommendations

The majority of the significant limitations experienced during the implementation of the developed solution were unpredictable incidents or variations in operations. Such instances were either accidents or unplanned maintenance or unavoidable work that had to take place. Such limitations can only be accounted for with appropriate safety factors in the calculation of any forecast or theoretical values.

One of the other primary limitations encountered was the IT policies of the case study mines that prohibited the use of some functions in the SCADA that would have improved the accuracy of implementation. It is recommended that such permissions be obtained from the mine as the ability to automate any task would add noticeable value.

The study only considered the four most popular and commonly used automated control strategies as seen in literature. There are additional automated control strategies such as using VSDs, for example, the use of which is widespread in industry. It is recommended that such strategies be added to the tables for consideration on systems where they may be applicable.

The developed solution was only implemented on compressed air ring systems and was assumed to be similarly effective on stand-alone systems. However, it is recommended that the solution be implemented on stand-alone systems to investigate the effect thereof and the solution suitability for such systems.

This study observed similarities in the operational schedules of several mining systems. It is recommended that further studies investigate the relationship between standard work hours, Eskom's time-of-use schedule, and the mining operational schedules.

Multiple sections of this study included limited statistical analysis where necessary for the development of baselines or targets and the evaluation of results. Future studies are

recommended to investigate the normality of frequency distributions for system parameters such as pressures as discussed in Section 3.2.1.2. It is also recommended that the scaled impact of statistical relevance filtering be investigated and the use of statistical hypothesis testing from Section 3.2.2.3 be expanded upon. However, it is highly recommended to investigate the existence of similarity laws between case studies that may allow for the development of characteristic curves for similar systems.

Finally, this study only saw the implementation of one iteration of the developed solution. As the systems are updated or changed over time, the solution can be reimplemented to improve the existing control. It is recommended that a follow-up study be conducted as the system infrastructure underwent not one but two significant phases of improvement since the beginning of the study in 2019.

4.4 Closure

The increasing electrical operating costs of South African mines at above-inflation rates are a great cause for concern. The widely used compressed air systems are significant contributors to these costs. This coupled with severe inefficiencies makes compressed air systems ideal candidates for the implementation of energy efficiency solutions. A need, therefore, existed for a simplified methodology that used the fundamental principles behind popular automated compressed air control strategies to achieve energy savings.

A solution methodology was successfully developed and used to identify, implement, and evaluate control strategies within system limitations. This resulted in no direct changes to the system infrastructure and thus avoided the associated capital cost involved. The solution was verified by the calculation of theoretical and actual energy savings during implementation on the case study systems. The results addressed the problem statement and satisfied the study objectives and thus validated the solution.

It is recommended that future studies first pursue automation, expand on the available control options, seek to implement the solution on various systems, and continuously reimplement the solution as systems improve.

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APPENDIX A: ADDITIONAL FIGURES

This appendix provides additional figures as referred to in the text.

Appendix A-1: Case study – System A-1 figures

Figure A-1 shows the projected and theoretical flows for System A-1 from Section 3.2.2.1.

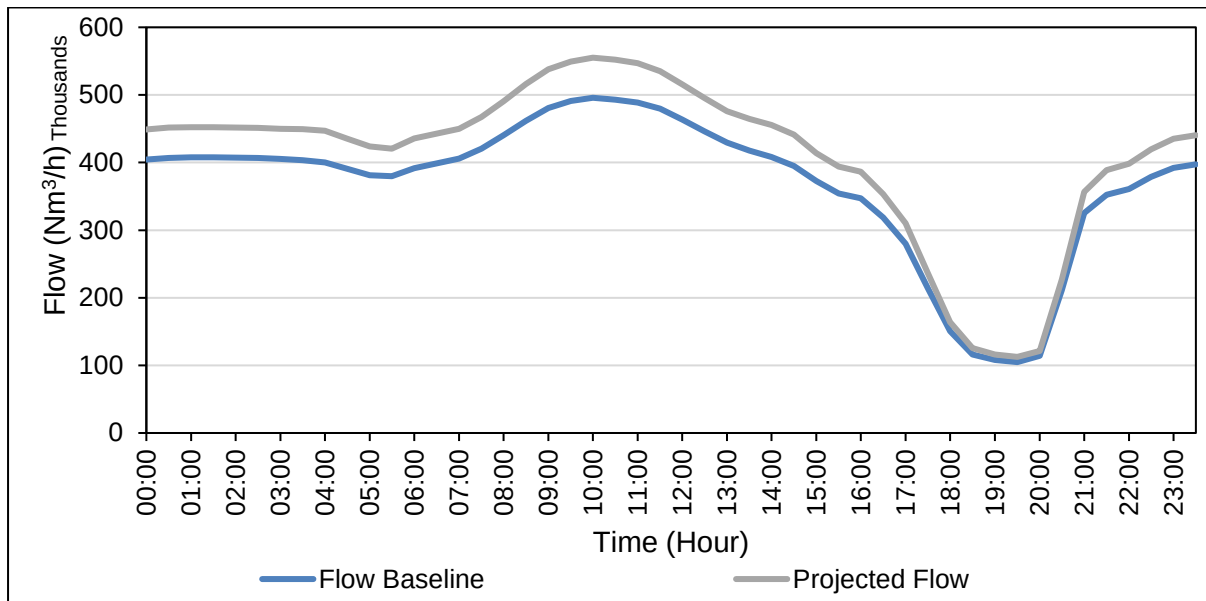


Figure A-1: System A-1 projected and theoretical flows

These flows were used to produce the corresponding power profiles and thus the theoretical savings values for verifying the solution.

Appendix A-2: Case study – System B-1 figures

Figure A-2 shows the projected KPI profile for System B-1 from Section 3.3.2.1.

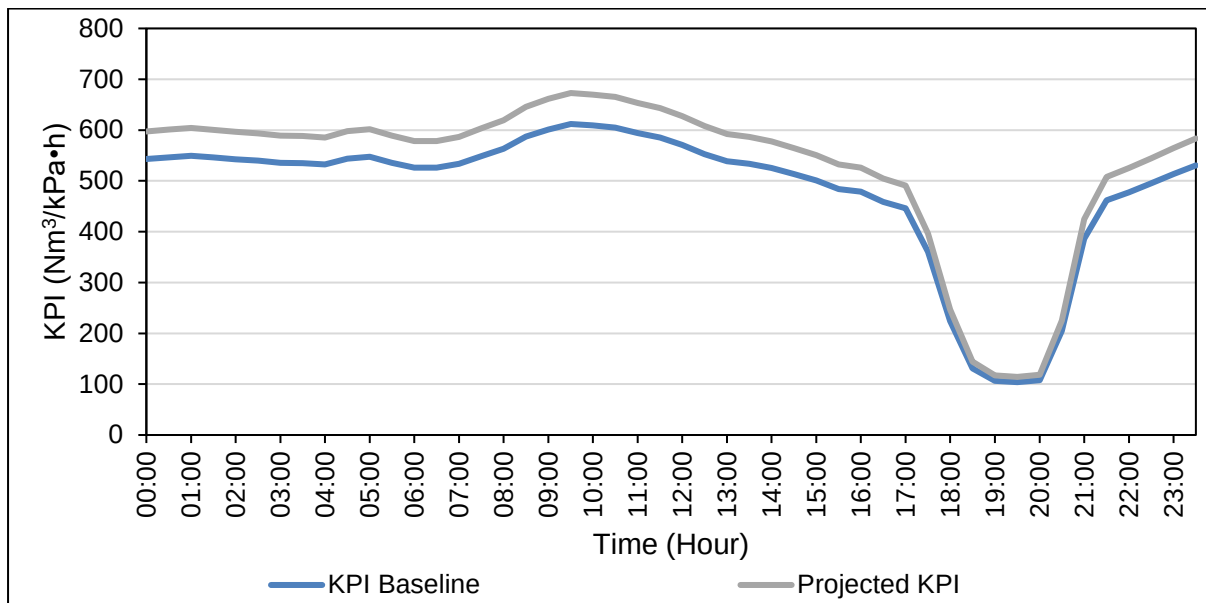


Figure A-2: System B-1 KPI baseline and projected KPI

The projected KPI values were used to produce the projected and theoretical flows. Figure A-3 shows the theoretical specific power profile for System B-1.

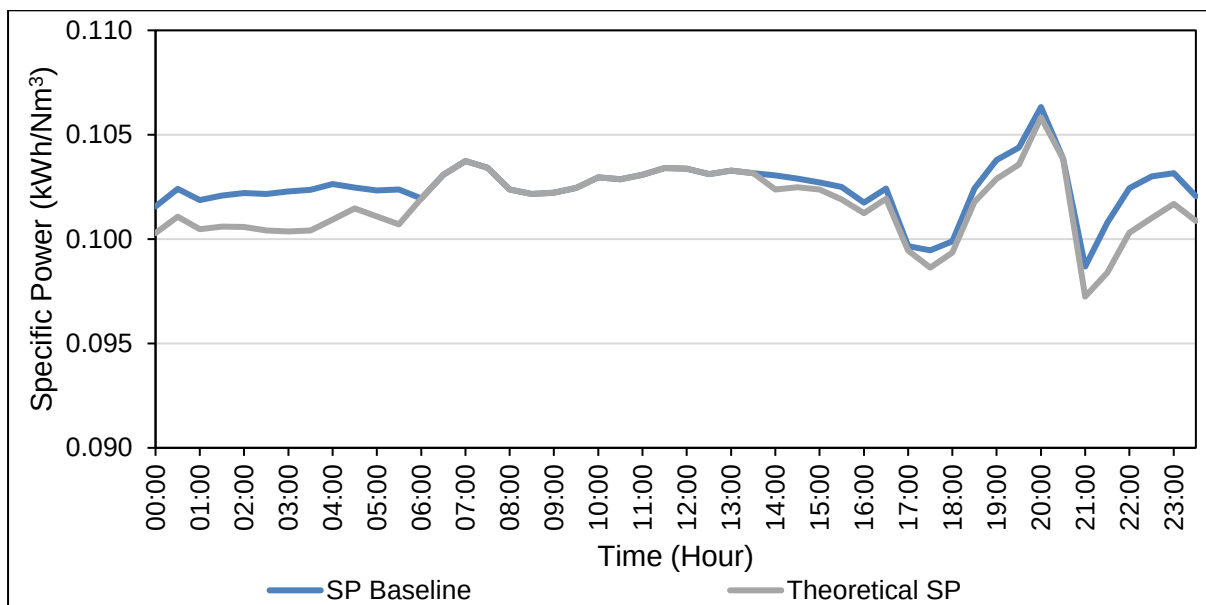


Figure A-3: System B-1 specific power baseline and theoretical specific power

The theoretical specific power values were used to produce the projected and theoretical powers. Figure A-4 shows the projected and theoretical flows for System B-1.

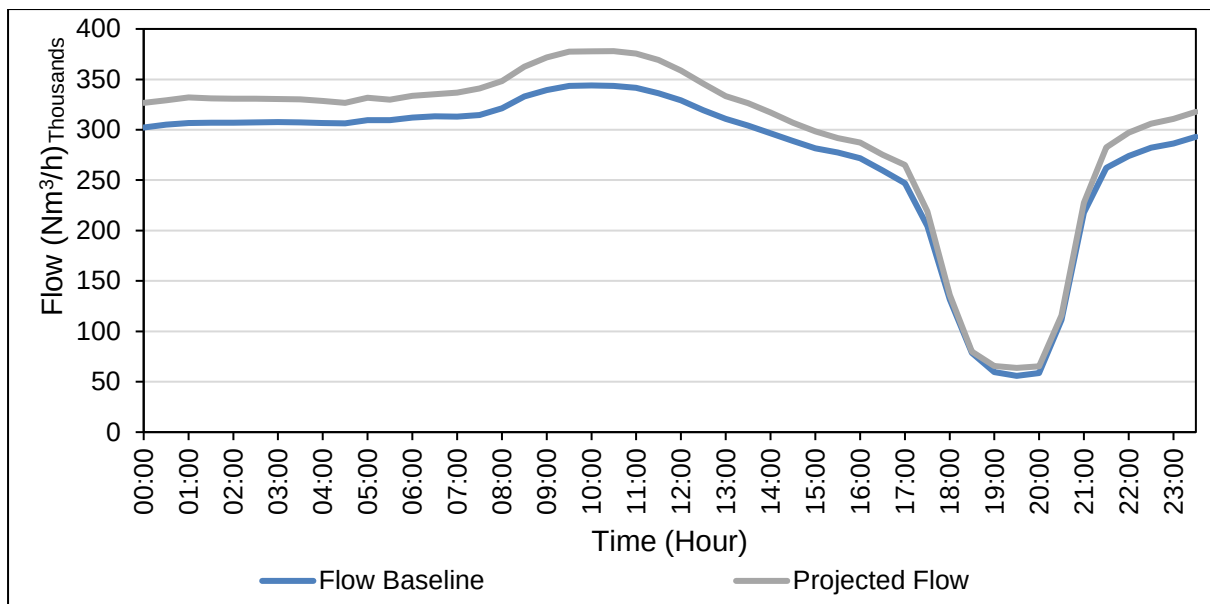


Figure A-4: System B-1 projected and theoretical flows

These flows were used to produce the corresponding power profiles and thus the theoretical savings values used to verify the solution.

APPENDIX B: DATA SETS

This appendix provides the data sets as referred to in the text.

Appendix B-1: Case study – System A-1 data sets

Table B-1 provides the projected and theoretical power data for System A-1 from Section 3.2.2.1 in kilowatt.

Table B-1: System A-1 projected and theoretical power data

Time	Projected Power	Theoretical Power
00:00	46 920.71	42 321.45
00:30	47 225.48	42 400.80
01:00	47 354.08	42 417.72
01:30	47 397.74	42 302.59
02:00	47 401.22	42 081.53
02:30	47 262.51	41 710.69
03:00	47 149.62	41 256.26
03:30	47 112.24	40 337.48
04:00	47 068.16	42 139.84
04:30	45 920.03	40 498.02
05:00	44 881.50	39 520.16
05:30	44 582.88	41 438.99
06:00	45 449.27	45 449.27
06:30	46 248.61	46 248.61
07:00	47 068.53	47 068.53
07:30	48 912.97	48 912.97
08:00	51 239.68	51 239.68
08:30	53 180.08	53 180.08
09:00	56 533.96	56 533.96
09:30	58 171.50	58 171.50
10:00	58 976.63	58 976.63

Time	Projected Power	Theoretical Power
10:30	58 887.71	58 887.71
11:00	58 406.18	57 731.21
11:30	57 549.05	56 548.38
12:00	55 507.85	54 490.46
12:30	53 180.08	53 180.08
13:00	50 892.58	50 892.58
13:30	49 439.65	49 439.65
14:00	48 282.63	46 420.68
14:30	46 578.72	44 267.24
15:00	43 744.56	42 255.25
15:30	41 827.44	40 539.24
16:00	40 443.47	39 367.81
16:30	36 916.80	35 345.40
17:00	31 753.65	30 239.58
17:30	24 055.67	23 043.85
18:00	16 929.07	16 134.48
18:30	13 186.86	12 709.61
19:00	12 244.98	11 754.57
19:30	11 887.59	11 336.78
20:00	12 722.36	12 449.40
20:30	22 568.68	22 568.68
21:00	35 646.80	33 064.76
21:30	40 269.10	36 452.99
22:00	41 480.83	37 569.37
22:30	43 266.39	39 613.76
23:00	45 127.62	41 061.33
23:30	45 905.16	41 569.89

This data was used to produce the theoretical savings values for verifying the solution.

Appendix B-2: Case study – System B-1 data sets

Table B-2 provides the projected and theoretical power data for System B-1 from Section 3.3.2.1 in kilowatt.

Table B-2: System B-1 projected and theoretical power data

Time	Projected Power	Theoretical Power
00:00	33 174.53	31 154.15
00:30	33 719.70	31 583.81
01:00	33 819.30	31 579.59
01:30	33 798.80	31 414.37
02:00	33 812.36	31 202.59
02:30	33 782.66	30 992.86
03:00	33 792.30	30 750.31
03:30	33 810.07	30 718.02
04:00	33 720.83	31 017.50
04:30	33 462.78	31 858.77
05:00	33 929.64	31 934.31
05:30	33 781.75	31 131.44
06:00	33 998.66	33 998.66
06:30	34 563.24	34 563.24
07:00	34 927.66	34 927.66
07:30	35 259.36	35 259.36
08:00	35 637.31	35 637.31
08:30	37 052.90	37 052.90
09:00	38 009.34	38 009.34
09:30	38 666.29	38 666.29
10:00	38 892.02	38 892.02
10:30	38 881.14	38 881.14
11:00	38 710.86	38 710.86
11:30	38 195.60	38 195.60

Time	Projected Power	Theoretical Power
12:00	37 088.16	37 088.16
12:30	35 636.86	35 636.86
13:00	34 433.40	34 433.40
13:30	33 650.73	33 650.73
14:00	32 683.90	31 637.44
14:30	31 576.04	30 946.58
15:00	30 643.05	30 165.12
15:30	29 886.65	29 016.28
16:00	29 235.20	28 507.95
16:30	28 180.66	27 521.95
17:00	26 403.74	26 114.60
17:30	21 788.61	20 911.98
18:00	13 607.32	13 249.63
18:30	8 187.66	7 934.38
19:00	6 814.83	6 521.79
19:30	6 651.58	6 394.84
20:00	6 931.95	6 770.81
20:30	12 013.96	12 013.96
21:00	22 448.45	20 854.60
21:30	28 461.34	25 242.40
22:00	30 423.59	27 400.77
22:30	31 519.74	28 591.36
23:00	32 071.26	29 857.34
23:30	32 440.04	30 609.52

This data was used to produce the theoretical savings values for verifying the solution.

APPENDIX C: DERIVATION OF EQUATIONS

This appendix provides the derivation of equations as referred to in the text.

Appendix C-1: Ideal gas law

Equation C-1 provides the ideal gas law for the derivation of Equation 2-3.

Equation C-1: Ideal gas law

$$pV = nRT$$

$$p = \text{Pressure} \quad [kPa]$$

$$V = \text{Volume} \quad [m^3]$$

$$n = \text{Number of moles in the gas} \quad [-]$$

$$R = \text{Gas constant} \quad [kJ/mol \cdot K]$$

$$T = \text{Temperature} \quad [K]$$

Equation C-1 can be rearranged to form Equation C-2 to evaluate the pressurised molar flow.

Equation C-2: Ideal gas law rearranged

$$\frac{n}{p} = \frac{V}{RT}$$

n = *Number of moles in the gas* [-]

p = *Pressure* [kPa]

V = *Volume* [m^3]

R = *Gas constant* [kJ/mol · K]

T = *Temperature* [K]

Equation C-2 can be applied to two scenarios on the same system at two different pressures. Equation C-3 shows this for the first scenario at time 1.

Equation C-3: Ideal gas law at time 1

$$\frac{n_1}{p_1} = \frac{V_1}{RT_1}$$

n_1 = *Number of moles in the gas at time 1* [-]

p_1 = *Pressure at time 1* [kPa]

V_1 = *Volume at time 1* [m^3]

R = *Gas constant* [kJ/mol · K]

T_1 = *Temperature at time 1* [K]

Equation C-4 shows the same application for the second scenario at time 2.

Equation C-4: Ideal gas law at time 2

$$\frac{n_2}{p_2} = \frac{V_2}{RT_2}$$

n_2	=	<i>Number of moles in the gas at time 2</i>	$[-]$
p_2	=	<i>Pressure at time 2</i>	$[kPa]$
V_2	=	<i>Volume at time 2</i>	$[m^3]$
R	=	<i>Gas constant</i>	$[kJ/mol \cdot K]$
T_2	=	<i>Temperature at time 2</i>	$[K]$

Assuming that the volume through which the air flows remains constant with constant temperature, the two equations pertaining to the scenarios can be set equal to each other. This is shown in Equation C-5.

Equation C-5: Pressurised molar flow balance

$$\frac{n_1}{p_1} = \frac{n_2}{p_2}$$

n_1	=	<i>Number of moles in the gas at time 1</i>	$[-]$
p_1	=	<i>Pressure at time 1</i>	$[kPa]$
n_2	=	<i>Number of moles in the gas at time 2</i>	$[-]$
p_2	=	<i>Pressure at time 2</i>	$[kPa]$

When measured flow is normalised to atmospheric conditions, it produces the nominal flow which is equivalent to molar flow. This leads to Equation C-6.

Equation C-6: Ideal gas law derivation of resistance to pressurised flow

$$\frac{\dot{Q}_1}{p_1} = \frac{\dot{Q}_2}{p_2}$$

$\dot{Q}_1$	=	Nominal flow at time 1	[Nm ³ /h]
p_1	=	Pressure at time 1	[kPa]
$\dot{Q}_2$	=	Nominal flow at time 2	[Nm ³ /h]
p_2	=	Pressure at time 2	[kPa]

Thus, concluding the derivation of Equation 2-3.

Appendix C-2: Compressor power

Equation C-7 is adapted from Equation 2-2 and provides the compressor power where the mass flow rate is substituted by the nominal flow rate and air density under standard conditions. As the nominal flow rate is used, all inlet conditions are set to standard conditions for the derivation of Equation 2-7.

Equation C-7: Compressor power

$$P = \frac{\dot{Q} \rho_{sc} C_p T_{in,sc} \left(\left(\frac{p_{out}}{p_{in,sc}} \right)^{\frac{k-1}{k}} - 1 \right)}{\eta_{comp}}$$

P	=	<i>Electrical compressor power</i>	[kW]
$\dot{Q}$	=	<i>Nominal flow</i>	[m ³ /h]
ρ_{sc}	=	<i>Air density at standard conditions</i>	[kg/m ³]
C_p	=	<i>Molar specific heat of air</i>	[J/kg · K]
$T_{in,sc}$	=	<i>Standard conditions inlet air temperature</i>	[K]
p_{out}	=	<i>Discharge air pressure</i>	[kPa]
$p_{in,sc}$	=	<i>Standard conditions inlet air pressure</i>	[kPa]
k	=	<i>Specific heat ratio of air</i>	[–]
η_{comp}	=	<i>Compressor efficiency</i>	[–]

Equation C-7 can be rearranged to produce Equation C-8. This is done by dividing both sides of Equation C-7 by the nominal flow, which produces the formula for compressor specific power.

Equation C-8: Compressor specific power

$$SP = \frac{\rho_{sc} C_p T_{in,sc} \left(\left(\frac{p_{out}}{p_{in,sc}} \right)^{\frac{k-1}{k}} - 1 \right)}{\eta_{comp}}$$

SP = Compressor specific power [kW · h/m³]

ρ_{sc} = Air density at standard conditions [kg/m³]

C_p = Molar specific heat of air [J/kg · K]

$T_{in,sc}$ = Standard conditions inlet air temperature [K]

p_{out} = Discharge air pressure [kPa]

$p_{in,sc}$ = Standard conditions inlet air pressure [kPa]

k = Specific heat ratio of air [–]

η_{comp} = Compressor efficiency [–]

Equation C-8 can be rearranged to make the compressor efficiency the subject of the formula as shown in Equation C-9.

Equation C-9: Compressor efficiency

$$\eta_{comp} = \frac{\rho_{sc} C_p T_{in,sc} \left(\left(\frac{p_{out}}{p_{in,sc}} \right)^{\frac{k-1}{k}} - 1 \right)}{SP}$$

η_{comp}	=	Compressor efficiency	[–]
ρ_{sc}	=	Air density at standard conditions	[kg/m ³]
C_p	=	Molar specific heat of air	[J/kg · K]
$T_{in,sc}$	=	Standard conditions inlet air temperature	[K]
p_{out}	=	Discharge air pressure	[kPa]
$p_{in,sc}$	=	Standard conditions inlet air pressure	[kPa]
k	=	Specific heat ratio of air	[–]
SP	=	Compressor specific power	[kW · h/m ³]

Now consider the scenario where a theoretical future specific power value must be calculated but the compressor efficiency is unknown. The theoretical specific power equation is shown in Equation C-10.

Equation C-10: Theoretical compressor specific power

$$SP_T = \frac{\rho_{sc} C_p T_{in,sc} \left(\left(\frac{p_{out,T}}{p_{in,sc}} \right)^{\frac{k-1}{k}} - 1 \right)}{\eta_{comp}}$$

SP_T = Theoretical compressor specific power [kW · h/m³]

ρ_{sc} = Air density at standard conditions [kg/m³]

C_p = Molar specific heat of air [J/kg · K]

$T_{in,sc}$ = Standard conditions inlet air temperature [K]

$p_{out,T}$ = Theoretical discharge air pressure [kPa]

$p_{in,sc}$ = Standard conditions inlet air pressure [kPa]

k = Specific heat ratio of air [–]

η_{comp} = Compressor efficiency [–]

By having a known baseline specific power value and its conditions, the baseline efficiency equation can be populated as efficiency is expected to remain constant. The baseline efficiency is shown in Equation C-11.

Equation C-11: Compressor efficiency baseline

$$\eta_{comp} = \frac{\rho_{sc} C_p T_{in,sc} \left(\left(\frac{p_{out,B}}{p_{in,sc}} \right)^{\frac{k-1}{k}} - 1 \right)}{SP_B}$$

η_{comp}	=	<i>Compressor efficiency</i>	$[-]$
ρ_{sc}	=	<i>Air density at standard conditions</i>	$[kg/m^3]$
C_p	=	<i>Molar specific heat of air</i>	$[J/kg \cdot K]$
$T_{in,sc}$	=	<i>Standard conditions inlet air temperature</i>	$[K]$
$p_{out,B}$	=	<i>Baseline discharge air pressure</i>	$[kPa]$
$p_{in,sc}$	=	<i>Standard conditions inlet air pressure</i>	$[kPa]$
k	=	<i>Specific heat ratio of air</i>	$[-]$
SP_B	=	<i>Baseline compressor specific power</i>	$[kW \cdot h/m^3]$

Equation C-12 is obtained by substituting Equation C-11 into Equation C-10 and rearranging parts of the equation.

Equation C-12: Theoretical specific power

$$SP_T = SP_B \times \left(\frac{p_{out,T}^{\frac{k-1}{k}} \times p_{in,sc}^{\frac{1-k}{k}} - 1}{p_{out,B}^{\frac{k-1}{k}} \times p_{in,sc}^{\frac{1-k}{k}} - 1} \right)$$

SP_T = Theoretical specific power [kW · h/Nm³]

SP_B = Baseline specific power [kW · h/Nm³]

$p_{out,T}$ = Theoretical supply pressure [kPa]

k = Constant (1.4) —

$p_{in,sc}$ = Standard conditions inlet pressure [kPa]

$p_{out,B}$ = Baseline supply pressure [kPa]

Thus, concluding the derivation of Equation 2-7.