Analysing mine energy management considering utility demand

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ABSTRACT

Title: Analysing mine energy management considering utility demand

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Keywords: schedule adjustment; time-of-use; cost reduction; deep-level mine; integrated load management; specific energy; compressed air system; compressor; simplified method; energy

Abstract text

This dissertation was completed using an article-based format. Article 1 has been submitted to the *Journal of Energy in Southern Africa* and Article 2 to *Sustainable Energy Technologies and Assessments*.

In the past, the cost of electricity was not as significant as it is today. Therefore, it was not common practice for mining companies to take peak time-of-use tariffs into account for their shift schedules. The literature indicates a need for the analysis of mine energy management, focusing on utility demand. Mines have numerous utilities with varying power demands, which are mostly based on mining operation. Mining operation often varies from one day to the next despite the schedule being fixed, as this schedule is dependent on people. The schedules are dependent on people in that the underground workers use utilities for purposes that the schedules and shifts describe. This leads to variability in that different utilities have different purposes which align with the specific work done by underground mining personnel.

The overall study was conducted on the mining operation system of a South African platinum mine consisting of various mining shafts, focusing on the power demand of utilities in general and the compressed air system in particular.

Article 1

Throughout literature, no study has been reported where an entire mine was holistically analysed regarding utility power demand, using a top-down approach. Therefore, the objective of the study reported on in Article 1 was to analyse an entire mining operation system with the notion of

integrating load management with shift changes. This was achieved by analysing the power demand of the utilities, mine operational schedules and their interconnectedness.

The study indicated a potential power reduction of the studied system. The power demand reduction was statistically estimated using the average power demand reductions from existing studies that were conducted on mines. The demand reductions were applied to the power demand of the utilities when specific shifts at the shafts aligned. Firstly, a maximum savings scenario was determined. The resulting operation schedule change was estimated to result in a 1.3% reduction in the total electricity costs of the mine. Furthermore, system operational improvements were simulated and had a potential total reduction effect of 8.4%, which was primarily attributed to a reduction in compressor power demand.

The implications (large adjustments in shaft operations and shifts starting at difficult times) of the proposed schedule adjustments (that entails adjusting shift starting times at different shafts on the mine to align with other shafts on the same mining system, and to account for higher cost time-of-use times) necessitated the simulation of a realistic scenario. This was necessitated because drastic adjustments in shaft operations are not necessarily feasible and shifts start at improbable times according to shift descriptions.

The realistic scenario showed an electricity cost reduction of 0.7% resulting from only schedule adjustments. The realistic schedule adjustment, however, revealed possibilities for further system operational improvements. When these operational improvements were simulated on the relevant utilities, the effect was a potential total reduction of 7.6%.

The operational improvements continuously used in this study include, as also previously described, the average reduction found from numerous studies on various utilities. This includes load shifts on pumping systems, peak clips on ventilation fans, improved control of compressors and refrigeration system utilities and it includes load shifts and improved scheduling of winders. This is just some of the power demand reductions included to achieve operational improvement.

Article 1 identified the need for further analyses of the relevant utilities. The compressor system was found to demand between 20% and 55% of utility power supplied to a mine based on literature and analysis of the case study system. It was, therefore, necessary to analyse this utility with regards to its performance, power demand and air supply.

Article 2

Mine compressed air systems are difficult to analyse due to their inefficiency and complexity. No clear method exists that can be used to characterise the total performance of the supply side system regarding air supply and utility power demand. Moreover, a simplified and unbiased performance measuring method was lacking in the literature. The objective of the study reported on in Article 2 was therefore to develop a simplified method that used a single metric (specific energy) to characterise the performance of a compressed air system relative to the compressed air supply and compressor power consumption. This metric required minimal data and can be used as a guide to improve performance.

A compressed air system was analysed before and after project implementation, using the simplified method. The projects included control optimisation, underlying compressor system improvement and energy efficiency projects. The simplified method gave a good indication of performance changes resulting from the abovementioned projects on the compressed air system, with an improvement of 6% on the average total specific energy, from 104 to 98 Wh/m^3. The non-drilling shift specific energy of the system decreased from 103 to 94 Wh/m^3, which constitutes a 9% improvement. The reduction in specific energy corresponds with an 8% reduction in power demand with only a 0.4% reduction in supplied flow. This study showed the possibility of characterising the performance of complex compressed air systems using a simplified metric. It can also be used to verify whether supply side initiatives were effective.

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LIST OF ARTICLES

This dissertation is based on the work described in the articles listed below, and it was deemed suitable to complete the dissertation in an article format. The following articles are appended with the permissions of the copyright holders. Article 1 has only been submitted. Article 2 has been published.

I. W.G. Shaw, M. Mathews, J. Marais, 'Holistic analysis of the effect on electricity cost when varying shift schedules according to time-of-use tariffs,' *Journal of Energy in Southern Africa*, 2018.

II. W.G. Shaw, M. Mathews, J. Marais, 'Using specific energy as a metric to characterise compressor system performance,' *Sustainable Energy Technologies and Assessments*, 2018.

The student, W.G. Shaw, was responsible for the technical content of each article. The dissertation was submitted with permission of the co-authors, namely Drs J.H. Marais and M.J. Mathews.

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CHAPTER 1 INTRODUCTION

[1]

The power challenge in South Africa is briefly covered in this chapter, as is the effect of time-of-use (TOU) tariffs on deep-level mining electricity costs. The mining utilities are discussed and their operation and power demand analysed. This informed the formulation of the research objective finally described, which was to analyse mine energy management considering utility power demand.

[1] SAIREC, 'SAIREC visits Eskom's Komati Power Station', 2017. [Online]. Available: http://www.sairac.co.za/index.php/100-news/307-sairac-visits-eskom-s-komati-power-station. [Accessed: 15 Oct. 2018].

1.1 BACKGROUND

The mining industry is under consistent financial pressure as the expenditure of mines is generally increasing, and precious metal prices do not necessarily follow the same upward trend. This has caused mines to employ various strategies to improve the operational efficiency of relevant systems [2]. Another unfortunate outcome of this situation is that, in some cases, mine executive personnel have found it financially necessary to retrench workers and close non-profitable mining shafts [3,4].

The latest annual 'Facts and Figures' report by the Minerals Council South Africa (released in September 2018) indicates that South African mines export 88% of the products from mining and refining processes [5]. Precious metal prices are therefore dependent on international demand. The demand has, however, not necessarily decreased, but the public valuation of precious metals has to a certain degree as illustrated in Figure 1, which shows the gold and platinum prices for the previous 18 years. Although these two precious metals underwent growth between 2000 and 2011, from August 2011, the precious metal price has been steadily decreasing.

[2] I. Solomons, 'Despite power supply stability, mine still prioritise efficient energy use,' *Mining Weekly*, 2016. [Online]. Available: http://www.miningweekly.com/article/energy-efficiency-remains-a-top-priority-for-miners-2016-09-02/rep_id:3650. [Accessed: 15 Aug. 2018].
[3] N. Lechela, 'Workers 'dumped' at Pan African's Evander 8 Shaft - NUM,' *fin24*, 17 May 2018. [Online]. Available: https://www.fin24.com/Companies/Mining/workers-dumped-at-pan-africans-evander-8-shaft-num-20180517. [Accessed: 15 Aug. 2018].
[4] M. Mataranyika, 'SA mine closures to weigh down global platinum supply,' *fin24*, 8 Mar. 2018. [Online]. Available: https://www.fin24.com/Companies/Mining/sa-mine-closures-to-weigh-down-global-platinum-supply-20180308. [Accessed: 15 Aug. 2018].
[5] Minerals Council of South Africa, 'Facts and Figures 2017,' 2018. [Online]. Available: http://www.mineralscouncil.org.za/industry-news/publications/facts-and-figures [Accessed: 10 Aug. 2018].

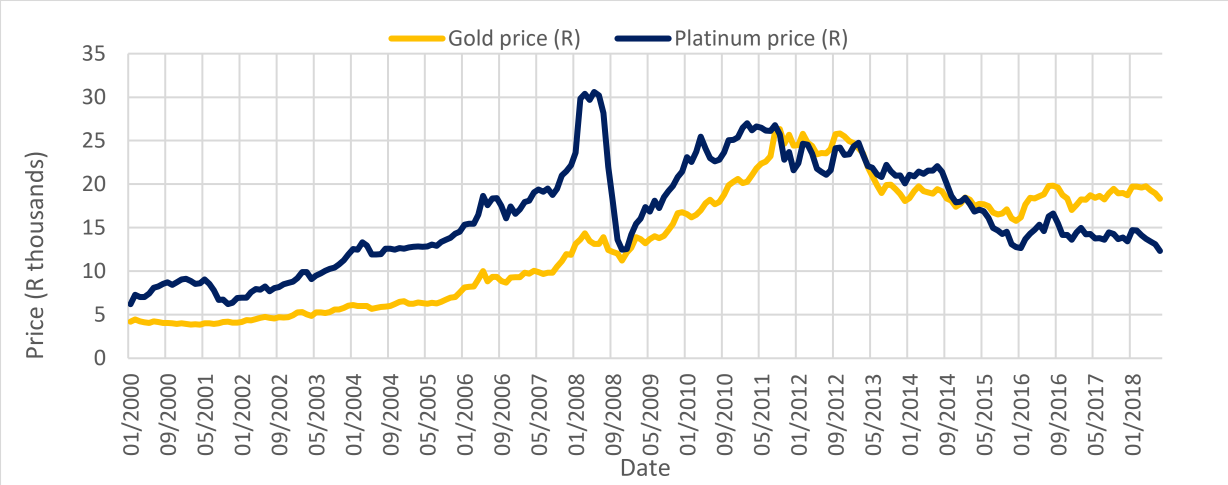


Figure 1: Gold and platinum stock prices from 2000 to 2018

Investors are not motivated to invest money in the South African industry according to Whitfield [6]. Without forthcoming overseas investors, an industry as large as the South African mining industry is bound to struggle financially, which contributes to the weak economic growth. The disinterest from foreign investors is linked to continuous strikes in the mining industry as expounded in the following paragraphs.

Bohlmann *et al.* measured the economy-wide impact of the 2014 labour strike in the platinum industry [1]. Supporting Whitfield's arguments, these authors found that the higher wages finally decided on did not cause the most economic damage [1]. Instead, the damage was caused by the reaction of industry investors towards the South African mining industry [1]. The effects of the 2014 labour strikes affected, according to Bohlmann *et al.*, a 0.7% reduction in the GDP, which would not recover to baseline in any of their simulations until 2020 [1].

However, damage to the mining industry is not only caused by the disinterest of investors but also by the increasing cost of electricity. Electricity costs amounted to between 11 and 17% of mining expenses in 2014 [2]. Baxter further indicated that electricity costs would increase to 17 and 23% for the platinum and gold industries, respectively, by 2018. The increasing electricity costs are reflected by the electricity tariffs charged by Eskom as the principal power supplier in South Africa. The effect of tariffs is described by Krogscheepers and Gossel [3], and one result that is especially important to this study is that electricity tariffs significantly affect production in platinum group metals mining. The

[6] B. Whitfield, 'A foreign mining investor on why he won't put money in SA,' *Business Insider*, 2018. [Online]. Available: https://www.businessinsider.co.za/sa-mining-is-too-hard-to-invest-in-says-this-global-executive-2018-6. [Accessed: 10 Aug. 2018].

study and its contributions are discussed in more detail later. The electricity tariff increases followed inflation levels until 2008, as illustrated in Figure 2. In 2008, South Africa entered an electricity crisis, as the supply fell short of the demand [7][4]. Over the previous 15 years (until 2018), a tariff increase of 138% resulted, compared to the 64% of inflation. Monyei *et al.* showed that there had been a steady decline in electricity consumption and household income per individual despite Eskom's continued investment in increasing electricity supply capacity [5]. This, in combination with Eskom's plans to close down 3516 MW of old and deteriorating power plants [5], has led to worrisome tariff projections in all sectors. [8]

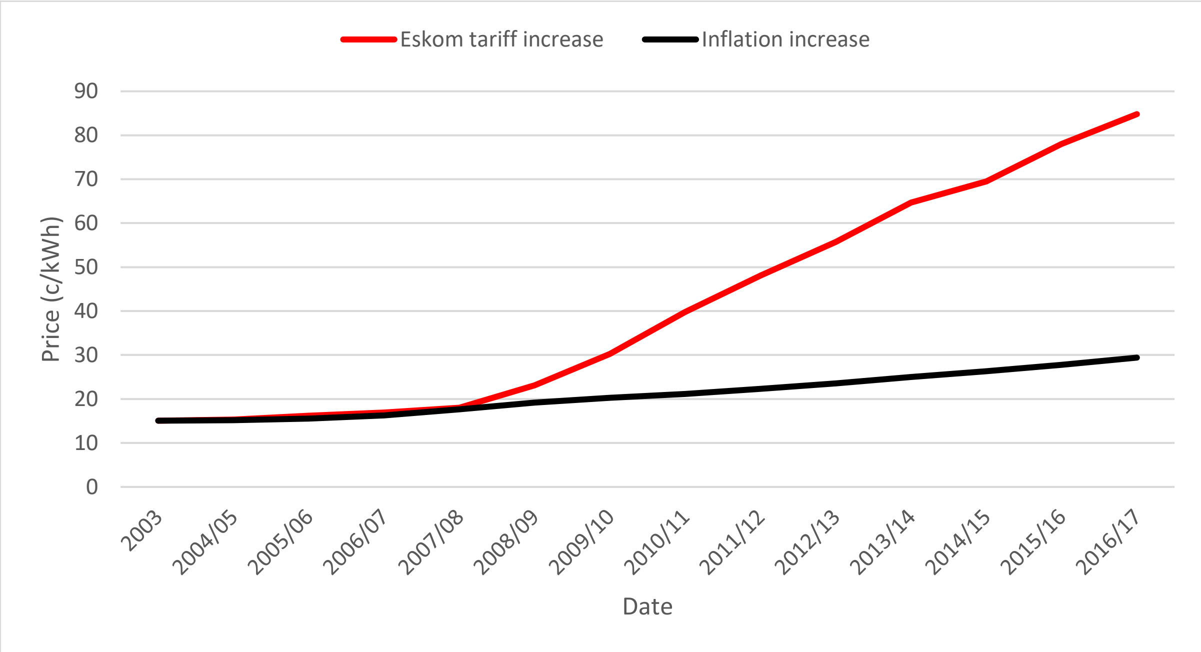


Figure 2: Average Eskom tariff compared to inflation in South Africa over the past 15 years

The typical tariff structure for South African industry is a TOU tariff structure, which is usually implemented to smooth the load curve [6]. This TOU tariff structure was initially implemented for industrial and large commercial consumers [6], but have now been expanded to residential consumers. Figure 3 illustrates the load curve which led to the implementation of TOU tariffs [7].

[7] J. Macharia, 'South Africa says still facing major energy crisis,' *Reuters*, 2009. [Online]. Available: https://www.reuters.com/article/us-safrica-power/south-africa-says-still-facing-major-energy-crisis-idUSTRE5315U320090402. [Accessed: 10 Aug. 2018].
[8] Business Report, 'Eskom want a 15% tariff increase,' *Business Report*, 2009. [Online]. Available: https://www.iol.co.za/business-report/energy/eskom-wants-a-15-tariff-increase-17599688. [Accessed: 3 Nov. 2018].

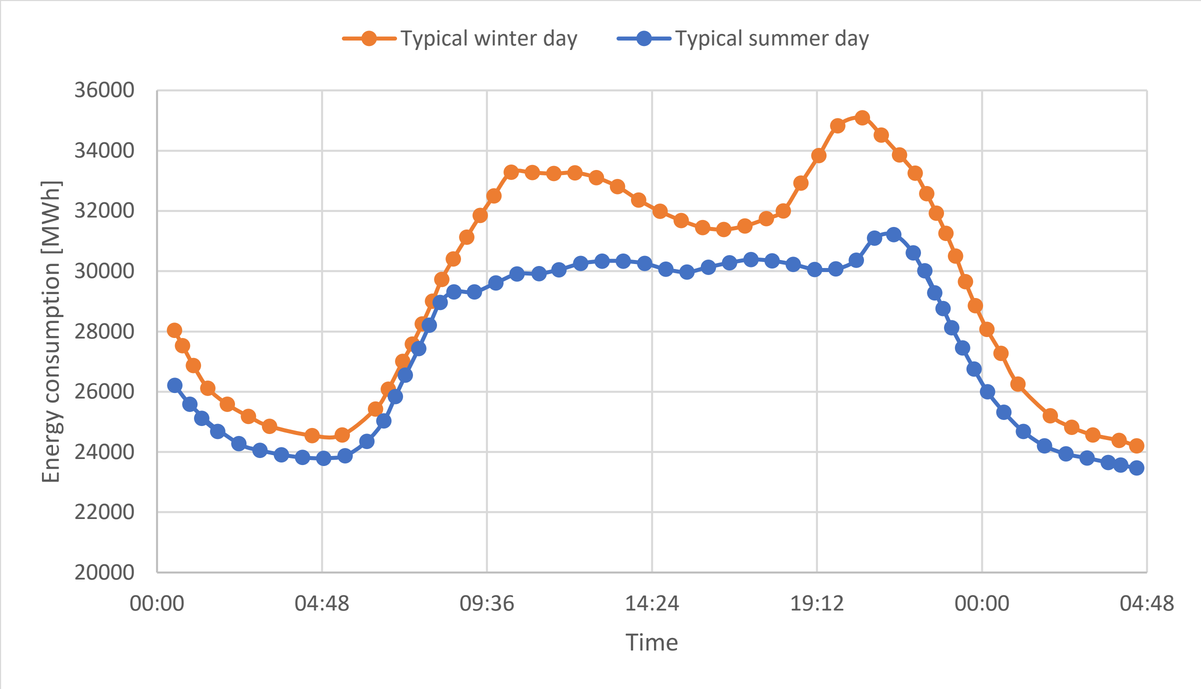


Figure 3: Average Eskom load profiles for winter and summer days, respectively [7]

Figure 3 illustrates the difference between load profiles for typical summer and winter days. There are distinct peaks, especially on winter days. The Eskom network is unable to supply sufficient power to satisfy the demand surges that is mainly caused by residential usage. This is caused by the difficulty to start-up and shut down power stations. Alternative, expensive systems are used to supply electricity during times of surging demand [8], which underscores the TOU tariff structure's validity during the prescribed times.

Figure 4 illustrates Eskom TOU tariffs regarding its MegaFlex tariff structure, which is the tariff structure applied to industrial energy consumers [9] for a distribution distance of less than 300 km. The MegaFlex structure consists of three types of tariffs. These tariffs are dependent on time and include peak, standard and off-peak pricing schedules [10]; they can also be distinguished in Figure 3. This is true especially of peak tariffs as clear peaks can be seen in Figure 3 from 08:00 to 11:00 and from 18:00 to 21:00. Standard tariff times can also be assimilated in Figure 3 from 11:00 to 18:00. TOU peak tariffs comprise approximately 20% of the hours of the day. The tariff increase from off-peak to peak time is especially substantial during winter months as illustrated by the dotted lines in Figure 4. The graphs in Figure 4 only illustrates the tariff schedule for winter and summer weekdays.

Figure 4: Eskom time-of-use tariff schedule and corresponding percentage price increases from summer off-peak to specific tariff used during the time of day [10]

Figure 4 illustrates that peak TOU tariffs can lead to substantial variations in electricity cost at a mine. These variations can lead to shafts operating inefficiently regarding electricity cost, especially if operations peak during peak times. Figure 4 illustrates each tariff time slot considering the Eskom TOU tariffs and the off-peak summer tariff. A 150% increase is noted during the winter peak TOU tariff compared to the off-peak summer TOU tariffs price.

The Eskom TOU tariffs are expected to continue an upward trend. This is because the mega power supplier is still consistently under pressure financially [9] as well from employees continually partaking in strikes, which occasionally lead to damage to property and threats to assets [10]. Dong, Ng and Cheng studied the difference between flat rate and TOU tariffs regarding their financial implications as well as the effect of different tariff structures [11]. It was found that customers (users) shifted their consumption from peak periods to non-peak periods in the case of TOU tariff structures [11]. Similar

[9] ESI Africa, 'Deadline looming for public on Eskom 30% tariff hike,' *ESI Africa*, 2018. [Online]. Available: https://www.esi-africa.com/deadline-looming-for-public-on-eskom-30-tariff-hike/. [Accessed: 15 Aug. 2018].
[10] fin24, 'Unions hold the cards as Eskom faces fresh strike threat,' *fin24*, 2018. [Online]. Available: https://www.fin24.com/Economy/Eskom/unions-hold-the-cards-as-eskom-faces-fresh-strike-threat-20180813. [Accessed: 15 Aug. 2018].

consumption trends are not usually witnessed at mines, where the operational schedule, which is mostly dependent on people working underground according to a defined shift schedule, does not heed the TOU tariffs [12], [13]. It may, however, be the case that energy-saving companies have implemented projects with regards to TOU tariff schedules [12], [13].

Granell, Axon and Wallom assessed businesses with regards to their energy usage [14]. The use of either static or flat rate tariffs and dynamic or TOU tariffs was assessed in the study [14]. These authors found that changing from fixed-price to TOU tariffs had the best financial outcomes for businesses [14]. The implication of the study by Granell, Axon and Wallom is that mines could and should maximise potential benefits from the TOU tariff structure although the tariff structure is not currently set up for their benefit.

Krogscheepers and Gossel [3] simulated the effect of sudden changes in one factor on other factors, including international factors (demand and prices) and domestic factors (salaries, electricity tariffs and output per employee), in a platinum group metals company. The simulation was implemented for platinum production, making use of impulse responses. The findings show that international factors causally affected domestic factors [3]. Production was found to be driven by platinum group metals price fluctuations, electricity tariffs and output per mine employee [3]. These results have one pertinent implication for the current study: The fact that production is significantly affected by power tariffs indicates the need for mining companies to invest in energy efficiency and potential alternative sources of electricity generation [3].

Variation in the mine energy profile occurs throughout a normal operational day, as the different systems or utilities, shown in Figure 5, are switched on and off and ramped up and down depending on the requirements underground. A utility, as defined in this study, is a mining component used to meet the ends of mining, that is, ore production. The most common mining utilities include compressors, pumps, refrigeration components, ventilation fans, winders and all underground components (e.g. winches and lighting). The variability in utility operation is mainly due to the different shifts and schedules used to facilitate underground mining [15], resulting in differing utility demands as each utility (Figure 5) is used during different times of the day and with varying power demands. The result is that some utilities are used more during certain times of the day or certain shifts.

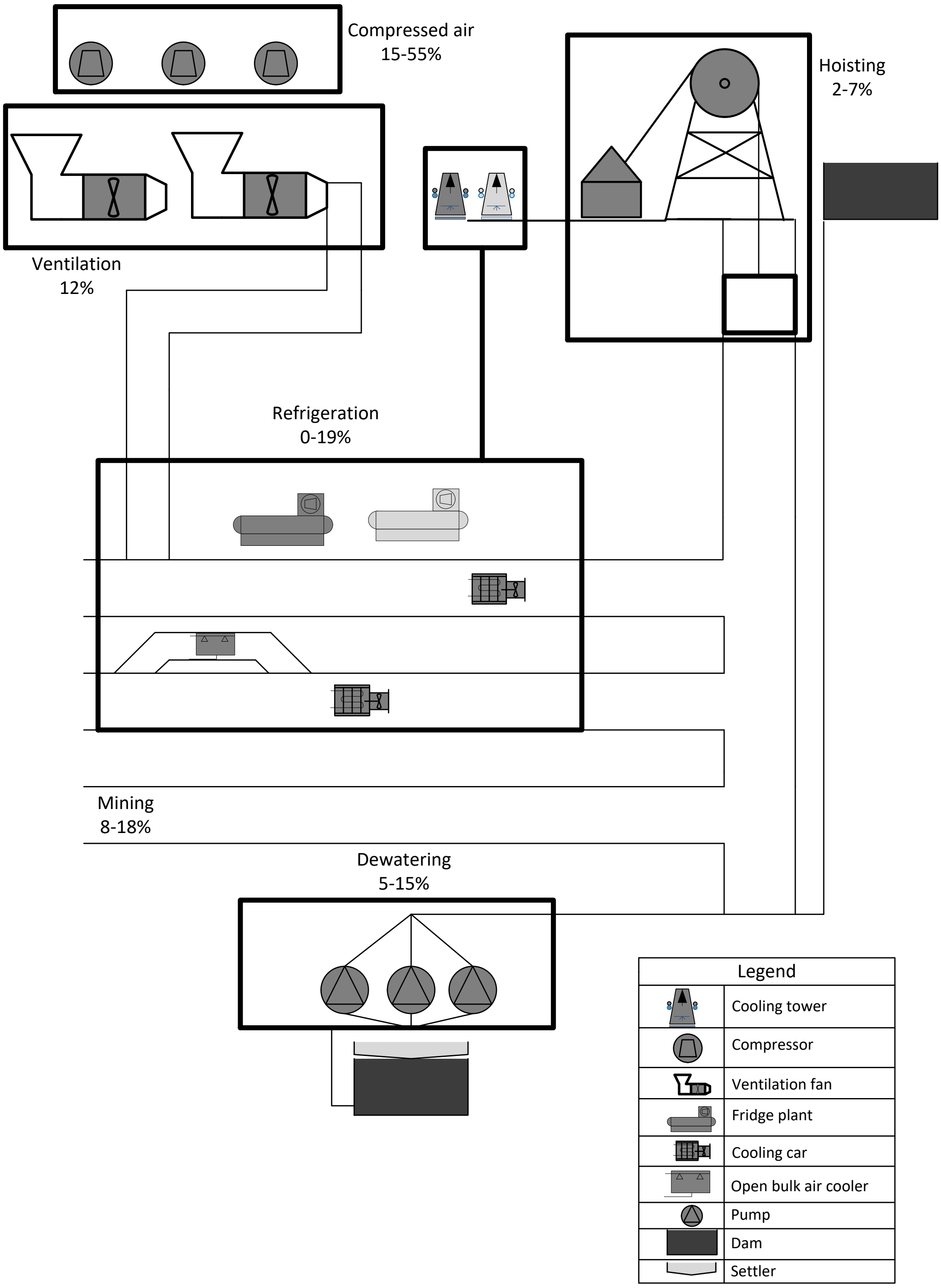


Figure 5: Typical electrical systems present on platinum and gold mines with the relative percentages of total power demand [16]

During the drilling shift, for instance, the compressed air system, as shown in Figure 5, is used near or at full capacity, and thus compressors are run at maximum power demand, which can be up to 55% of total mine utility power demand [15]. The ventilation fans are utilised throughout the day for underground ventilation and to extract dangerous gases from the mine after the blasting shift and can consume up to 12% of total utility power demand [15]. The winders are used when mining employees need to be transported up and down the shaft and for removing ore from below ground. Maximum winder utilisation usually occurs before and after drilling, during afternoon and night shifts, but winders used to hoist ore and waste are generally used 24 hours per day [15]. The winder power demand can range from 2% to 7% of the total mine utility power demand. Compressed air is used to a certain degree during the night shift when loaders are used to load ore and waste onto locomotives. Pumping systems are used whenever the dams at the bottom of the shaft reach specific levels, and water needs to be pumped out of the mine [15]. Pumping systems also make up part of refrigeration systems, which are only found on mines where natural ventilation is insufficient. This utility power demand can range from 5 to 15% of total mine utility power demand. In summary, mining occurs throughout the day, as previously mentioned, depends on different systems and power demand ranges from 8–18% of total mine utility power demand [16].

The literature review thus suggests that two problems exist, which are exemplified by Figure 6. Firstly, the escalating cost of electricity may become an increasingly significant problem for mining companies and can be exacerbated by the TOU tariffs. Secondly, the utility power demand is mainly dependent on mining operations, as mentioned above and illustrated in Figure 6. The mining operations are dependent upon people (workers), and in some cases, thousands of people and that may have to effect variability in the mining schedule and lead to an inability to align operations schedules while also adjusting for TOU tariff structures.

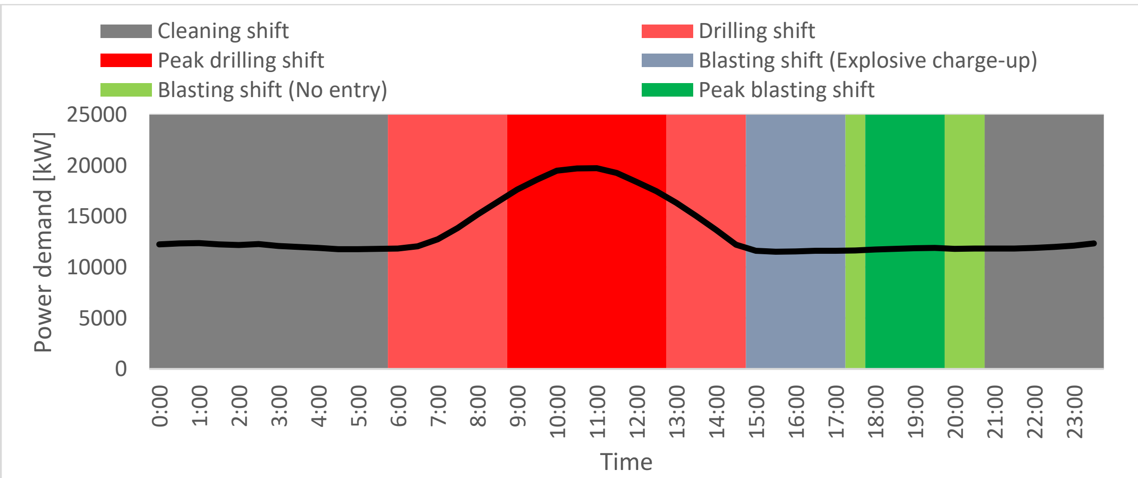


Figure 6: Typical compressor power profile of mine operational schedules adapted [17]

The research problem identified through the literature review can be described regarding the effect of TOU tariffs on mine utility cost. Utility power demand varies in consistency (and according to the mining operation schedule), and this may cause irregular power demand with regards to the TOU tariff schedule. According to existing research, the electricity tariffs may have a substantial effect on the success of a business, and, in South Africa, the future of the TOU tariff is still unclear, but numerous sources point to steep increases.

The research necessitated further investigation into an analysis of mine energy management regarding utility power demand.

1.2 DISSERTATION OVERVIEW

The dissertation overview provides a basic outline of each chapter:

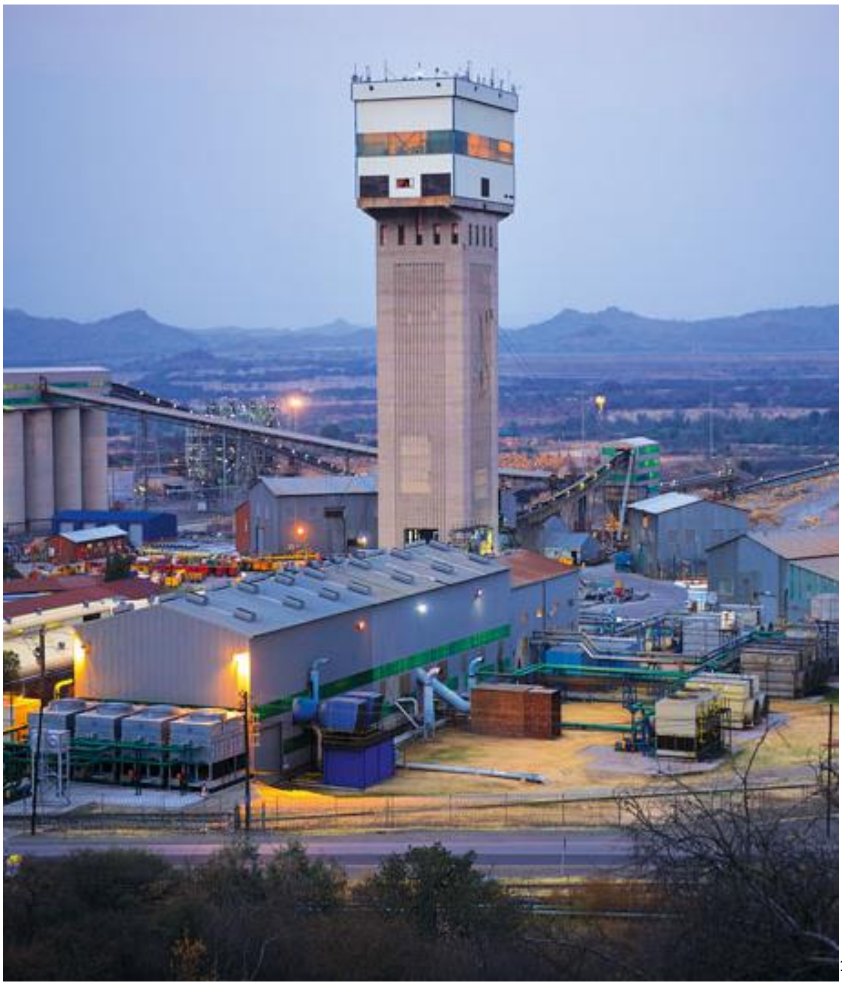
Chapter 1: Introduction – This chapter provides a summary and outline of the dissertation. The background information and literature that led to the formulation of the initial research objective which undergirded the two research articles. This leads to a basic understanding of the research theme, which is addressed in the subsequent chapters.

Chapter 2: Article 1 – The first study research problem and objective was determined after further analysis of the overarching problem found from the literature review, which led to the study reported on in the first article. The chapter consists of a literature review, a summary of the article and a discussion of the implications of the findings. The discussion elucidates the rationale behind the study reported on in the second article.

Chapter 3: Article 2 – The second study research problem and objective was addressed through a literature review, which informed the study reported on in the second article. The chapter consists of a literature review, a summary of the second article and a discussion on the implications of the findings.

Chapter 4: Conclusion – The concluding remarks are presented along with the final insights, salient implications and suggestions for future research.

CHAPTER 2 ANALYSIS OF MINE UTILITY POWER DEMAND AND THE ALIGNMENT OF OPERATIONAL SCHEDULES


[11]

This chapter reports on the holistic analysis of the mining system of a South African platinum mine and the corresponding utility power demand with regards to time-of-use (TOU) tariff times. The concept of aligning mining schedules to reduce power demand during high-cost TOU periods and reducing the overall utility demand was analysed through the study, and the simulation showed a substantial cost reduction. The article was a theoretical study and did not consist of any new implementation.

[11] Lonmin, 'Annual Report and Accounts / 2016,' 2016. [Online]. Available: https://www.lonmin.com/reports/2016/online_annual_report_2016/strategic_report/performance/operations.html. [Accessed: 15 Oct. 2018].

2.1 PREAMBLE

The previous chapter showed that TOU tariffs have significant effects on the power demand costs of mines in general. The differences between peak, off-peak and standard tariffs are substantial. The substantial difference between the tariff schedules has to affect that disregards for the TOU structures can have negative cost implications. The TOU tariff structures consequently need further investigation, especially in mining systems, where the utility power demand is high during peak and standard TOU times, which usually result from operation schedules that disregard TOU schedules.

The purpose of the following section is to discuss further and saturate the research problem that informed the first article through an in-depth review of the literature. The article written to solve the study problem was then described and summarised. Finally, the results are discussed and assessed regarding the objective described from the literature review.

2.2 LITERATURE REVIEW

Van der Zee found that electricity costs at a typical South African underground platinum mine in 2015 comprised approximately 24% of the total expenditure of the mine [18]. This amount can be divided into summer and winter use. The cost of electricity during summer peak TOU was approximately 30% of the total daytime electricity costs. Winter tariffs amounted to 50% of the total daytime electricity costs spent during the peak TOU period. However, the peak TOU hours only constitute 20% of the entire day. Furthermore, standard TOU tariffs consisted of 47% of the total expenditure in the summer and 36% of that in the winter. Finally, off-peak power costs accounted for 20% of the total expenditure during the summer and 13% during winter. This was determined by considering the average total cost of electricity over a year at a case-study mine. The cost was then compared to that generated during peak TOU tariff times in winter and summer. The same was done with the standard and off-peak tariffs. The substantial effect of TOU tariffs on the overall electricity cost has encouraged the implementation of numerous methods for reducing utility power demand and improving mine energy management.

Respective studies by De Kock, Els and Slade, have shown the effect of load management or demand-side management (DSM) initiatives on suitable pumping configurations, not only in mining systems but also at large municipal water treatment plants in the case of Els [19]. De Kock studied the long-term effects of DSM initiatives on South African mines [20], and Sadatiyan *et al.* indicated the effects of applying an optimiser tool to pump stations on the electricity usage and pollution emissions [21]. Similarly, Duvenhage *et al.* studied the integration of DSM interventions in bulk water supply strategies [22], and Schoeman *et al.* studied underground pump system optimisation through automation for cost savings [23]. Zhang and Zhuan studied the effect of optimising the operational schedule of multiple pump units [24]. Stols *et al.* studied the constraints of dewatering pumping systems and the cost savings achievable through improvement of these constraints [25].

The prevalence of these changes in power demand in different shifts has provided an opportunity for energy cost savings projects that take advantage of the TOU tariffs by shifting load to different times, as indicated by Storm, Gouws and Grobler on an irrigation pumping system [12] and Mohamed and Tariq, who reviewed different load management strategies [26]. A load shift requires the power demand and operations of a specific utility to be reduced during peak TOU tariffs [27]. In addition to load shifts, improved control philosophies are a method with which power demand has been reduced on mines, for example, Liebenberg, Velleman and Booysen [28].

Numerous studies have been conducted on improving systems relevant to the mining environment, namely pumping systems [19], [20], [22]–[25], [29], ventilation systems [15], [30]–[34], refrigeration systems [35]–[41], rock winder systems [27], [42]–[44], loco battery chargers [45], conveying systems [46], [47], jaw crushing systems [48], compressor systems [49]–[53] and mine shuttle cars [54].

Figure 7 and Figure 8 respectively illustrate a typical mine ventilation layout and refrigeration system with all its underlying components.

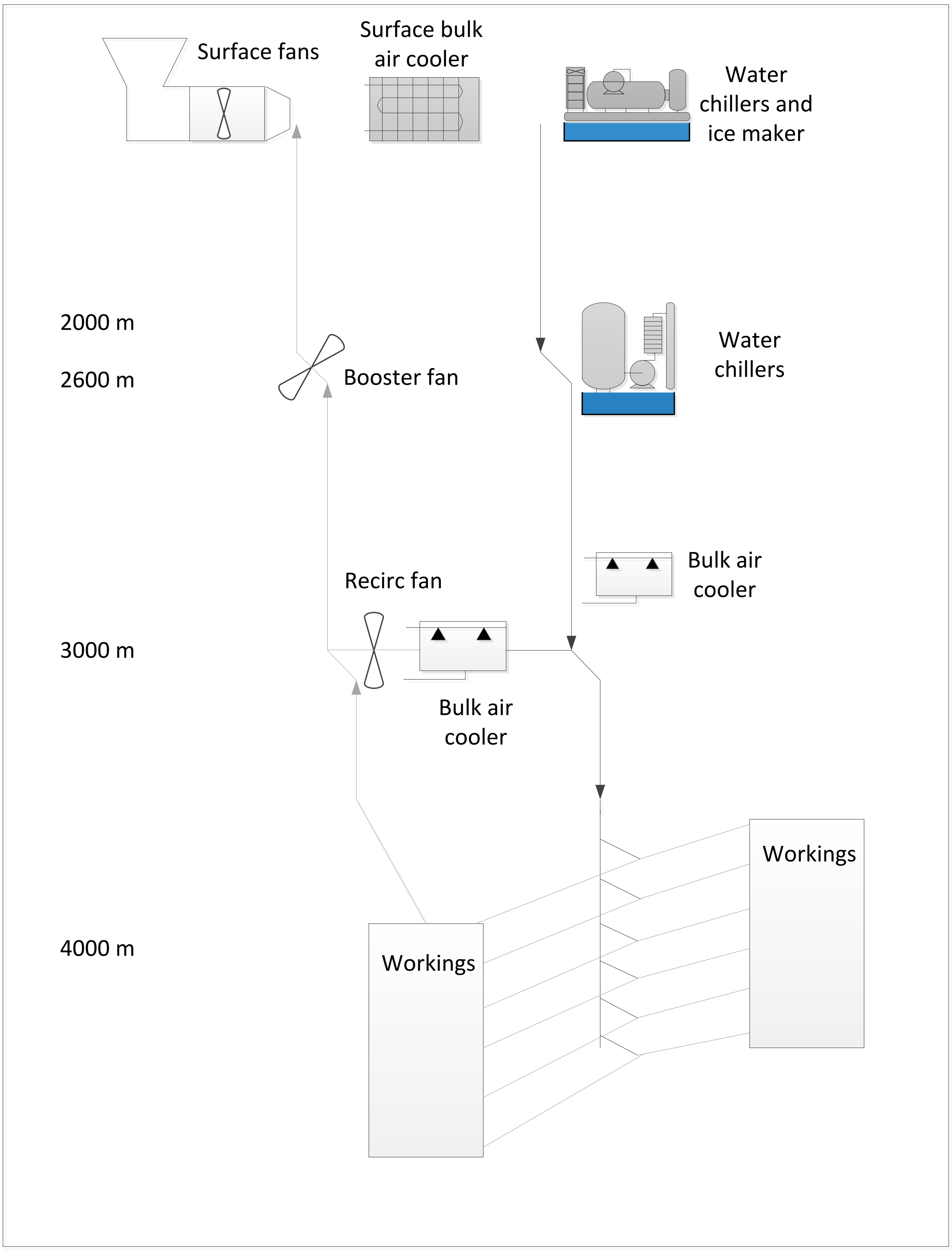


Figure 7: Typical deep mine ventilation layout [55]

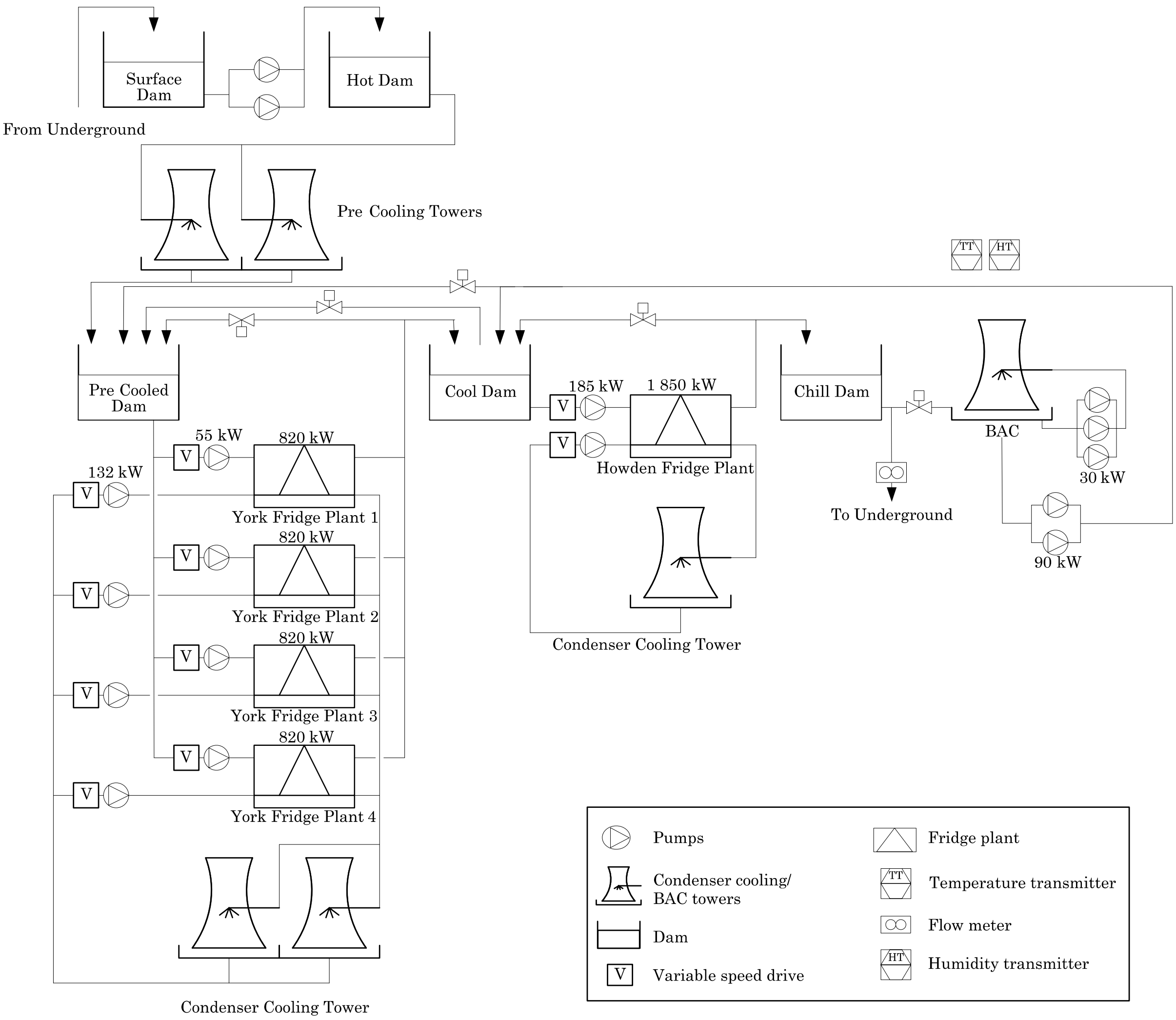


Figure 8: Typical mine refrigeration water reticulation system [40]

Pumping systems not only make out a large part of mine dewatering systems but are also a crucial part of refrigeration systems as illustrated in Figure 8. Chatterjee *et al.* accounted for the TOU tariffs and implemented a strategy to meet ventilation demands better and adjust for TOU tariffs [15]. Babu *et al.* studied the use of variable fan speed drives to ultimately reduce the power demand [31]. Engles *et al.* brought ventilation fans (Figure 7) and refrigeration systems (Figure 8) together and introduced control optimisations to an platinum mine cooling system using combined DSM strategies [30]. Van der Bijl looked at the introduction of sustainable DSM to a mine refrigeration system and the effects thereof [35]. Van Jaarsveld formulated a strategy that automatically controls deep-level mine bulk air coolers for power demand reductions during peak TOU times [40]. Schutte developed a model of a cascade mine surface refrigeration system that can be used in the abovementioned simulated system regarding DSM initiatives [38].

Furthermore, underground mining personnel need compressed air systems (CASs) to produce the necessary precious metals. CASs are used for various tasks underground, of which the most important is compressed air drilling [16]. These systems are some of the largest energy users, consuming approximately 10% of energy generated worldwide across all industries [50]. Marais *et al.* evaluated the efficiency of DSM initiatives on CASs. An average power demand reduction of 20.4 MW and an electricity cost saving of R74.6 million per annum was achieved at the case study mine, which is a favourable result [56]. Booysen found that CASs on platinum mines consume up to 40% of the total energy supplied to the mine [53]. This author developed a control strategy in which demand was matched with the supply, which reduced power demand [53]. Vittorini and Cipollone studied the financial effects that overall compressor replacement may have regarding the power demand reduction cost saving and the investment required to achieve said reduction [50]. The study discusses the substantial cost of compressed air generation [50]. Liebenberg *et al.* studied the effects on CASs and DSM potential of an automated control system, which operated at peak supply for an entire day [28]. The authors showed that there is potential for power demand reductions using demand-side initiatives on CASs [28]. From the discussion above, it can be concluded that (1) compressed air generation is expensive [50], (2) reduction of compressor power demand through compressor replacement may be expensive [50] but its implementation improves control, and (3) DSM strategies on these systems may lead to power reductions [28].

Another critical and frequently analysed system is rock hoisting systems. These systems usually consist of one or multiple winders, both at the surface and underground [27]. Two studies by Badenhorst *et al.* looked at the complexities associated with rock hoisting on mines. The results of these studies showed improvements in the control and scheduling of rock winders on deep-level mines regarding DSM and TOU tariffs [42], [44]. Buthelezi investigated the potential of load-shifting implemented in a deep-level mine rock winder system [27], using sequential automation to accomplish the load-shift [27]. Bosman further investigated the effect of winder motor control on other relevant energy consumers during peak TOU tariff times [57].

Practical experience suggests that the schedules of shafts vary in the same system [58]. Shaft schedules do not always enable a decrease in power demand during peak TOU times, and the differing schedules cause difficulties in the implementation of improvement projects. Misalignments between shaft schedules cause difficulty when improving the control philosophy of a specific utility. This is especially true when the component supplies multiple users [59].

Table 1 summarises existing research regarding mine power demand reduction projects. Shortcomings for the analysed systems regarding demand reduction and operational improvement projects are indicated. Table 1 also indicates the typical power demand reductions.

Table 1: Shortcomings (marked in red) and typical power demand reductions as indicated in the literature

Studies	System (no schedule change)									Integrated mining system and schedule change
	Pumping	Ventilation fans	Shuttle cars	Compressors	Rock winders	Loco battery chargers	Mine refrigeration systems	Jaw crushers	Conveying systems	
[13], [19]–[25], [29], [60]–[63]	X									
[15], [30]–[34], [55], [64]		X								
[30], [35]–[41], [65], [66]							X			
[27], [42]–[44], [67]					X					
[45]						X				
[46], [47]									X	
[48]								X		
[49]–[53], [68]–[72]				X						
[54]			X							
Typical power demand reduction [%]	50	40	-	25	57.5	46	45	34	10	

Previous studies have not focused on adjusting mine schedules; power demand reduction projects were only implemented on single systems or utilities. Moreover, different energy consuming utilities are dependent on different shifts in a mining environment. The dependence on shifts was shown by Chatterjee *et al.*, who analysed the different processes in the mining cycle according to the necessary ventilation airflow as part of their model [15]. Bosman and Van Rensburg also showed the dependence of loco battery charger power demand on the mine schedule [45], and Calitz showed the dependence of a mine refrigeration system on the schedule of mining operations [36]. The dependence of utilities on the operation schedule of a mine contributed towards the formulation of the research objective.

2.2.1 Article 1 study research problem and objective

A persistent problem was noted throughout literature. The need for a holistic energy management analysis and solution of a mine, persists.

The primary objective of the study reported on in Article 1 was to holistically analyse variable mine utility demand with regards to time-of-use schedules and the interconnection between different utilities, while also considering mine operation schedules. The study was theory based and used to test the possibility of implementation. This analysis suggested a possible intervention to reduce energy usage, along with its financial effects, in combination with power demand reduction initiatives through holistic energy management.

2.3 ARTICLE DESCRIPTION

2.3.1 Introduction

This study focused on a platinum mine in South Africa. This article was submitted to the *Journal of Energy in Southern Africa* and is currently awaiting the editor's feedback. See Appendix A for the article, titled 'Holistic analysis of the effect on electricity cost when varying shift schedules according to time-of-use tariffs', in its entirety. The following section provides a brief description of the methods and the essential findings of the study. The potential solution to the research objective is also described. A conceptual analysis strategy was finally discussed after the results of the study have been described, discussed and interpreted, which could be used to analyse entire mining systems with regards to integrated load management strategies.

2.3.2 Summary of methods

The different power-demanding utilities were isolated, and their power demand throughout a typical day was analysed. The analysis was done using a top-down approach where the energy supply was divided from a high level to lower levels (which consists of the different utilities). Furthermore, the power demand of each utility was analysed in light of its normal operation. The interconnection between different utilities was determined by analysing the relevant utilities used on a normal day, that is, based on the operation schedule of the mine. The interconnection was analysed by considering the various utilities that may be found operating during the same time-of-day.

An operational analysis was conducted. It combined a system characterisation with a pressure requirement analysis at all the relevant shafts as well as where the different shift schedules were determined from each of the relevant shafts in the mining operation system. The operational analysis was combined with a dependency analysis, wherein the power demand of each utility was analysed relative to the operational schedules of the various shafts. Finally, the actual data gathered were used to implement optimisations in terms of operational adjustments theoretically and to simulate further power demand reductions, control improvements and operational improvements (load management strategies), mainly via Microsoft Excel with an Office 365 subscription. The above-mentioned load management changes were simulated using the previously informed average load reductions found in literature as shown in Table 1. The reductions were simulated for when shaft operations aligned where they previously did not.

The results of the theoretical optimisation were evaluated based on several questions described in detail in the article, such as whether the adjustment is too large considering the production, whether the adjustment is realistic with regards to shift start and end times, whether shifts see daylight or not and whether the shifts at different shafts now align. The improvement simulations were done using specific equations shown in Appendix A lines 234, 235 and 245 and are described in detail in Article 1.

2.3.3 Summary of results

The first part of the theoretical operational analysis allowed schedule adjustments at the system shafts to be simulated using load reductions found through analysis of numerous sources. The corresponding power-demanding utilities dependent on the operational schedules at each shaft also underwent such simulated adjustments. The first analysis was done to achieve the maximum cost reduction of the baseline system compared to the adjusted system all the while using actual system data. The second scenario described a realistic schedule adjustment with less extensive adjustments (i.e. the realistic scenario).

A substantial difference between the two scenarios, not considering the hours of adjustment for each shaft, was the times during which the low-demand shifts occurred according to the adjusted schedules. The peak TOU tariff times occurred from 07:00 to 11:00 and 18:00 to 21:00 (Figure 9). The morning peak TOU tariff times aligned with the lower demand time of the maximum cost reduction scenario, which was also the longer peak TOU tariff period. However, the realistic scenario, aligned better with evening peak TOU tariff times (Figure 9).

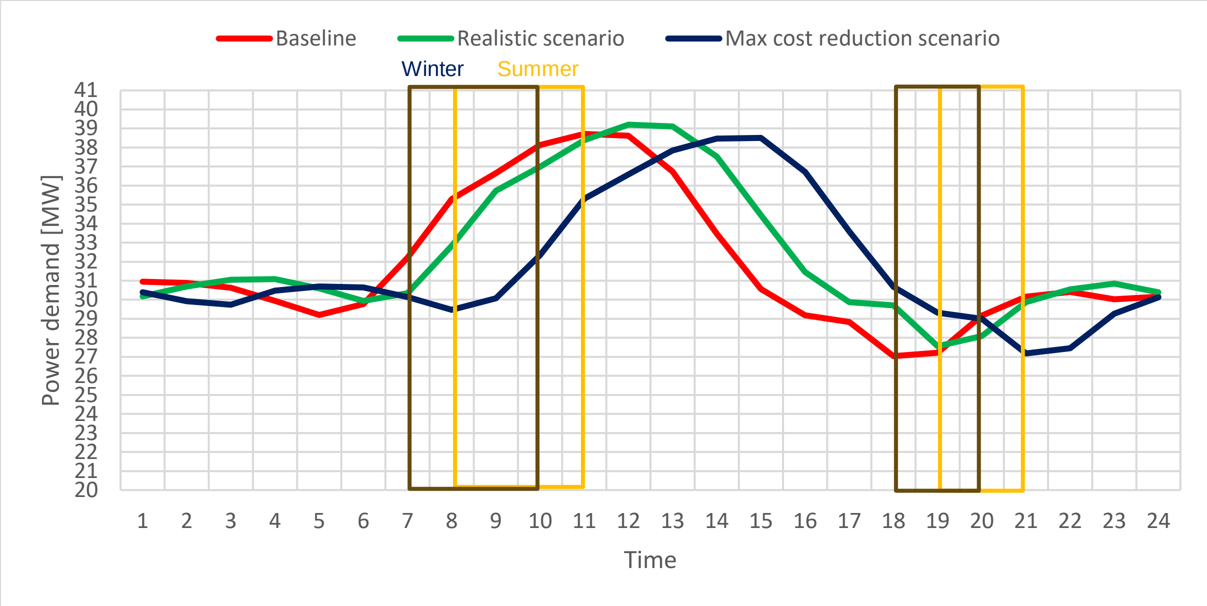


Figure 9: Comparison of the maximum cost reduction scenario and the realistic scenario power demand on a typical winter's and summer's weekday at a platinum mine

Both scenarios led to reduced power demand during either the morning (maximum cost reduction scenario) or the evening (realistic scenario) peak TOU tariff times (winter is dark yellow, and summer is yellow blocks) as illustrated in Figure 9. The improved schedule adjustment in both scenarios allowed further improvements to be simulated. The simulated improvements leading to power-demand reductions consisted of, but were not limited to, the following: fan peak clips, pump load shifts, compressed air and refrigeration control improvement and power demand reductions and winder schedule and control improvement. These improvements were justified from existing literature and described power demand reductions in the relevant systems at the different shafts, of which the average percentage reductions are indicated in Table 1. The reduced power demands in combination with the improved schedules are illustrated in Figure 10.

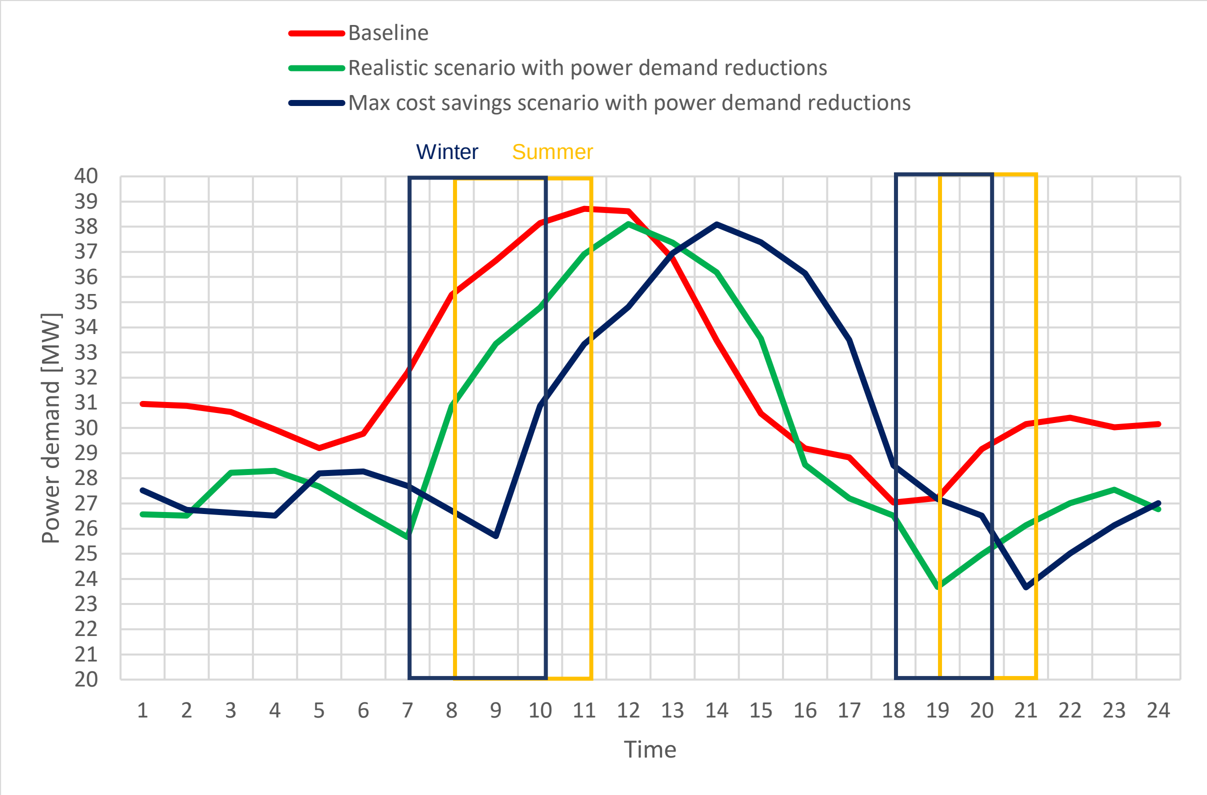


Figure 10: Maximum cost reduction and realistic scenarios with power demand reductions on a typical winter's and summer's day at a platinum mine

The financial implications of the schedule adjustments and simulated power demand reductions were necessary to complete the operational analysis. The cost reduction is shown in Table 2 as a percentage of the total energy cost per annum in the specific system. The total cost was calculated as approximately R160 million, only considering weekdays.

Table 2: Financial implications of proposed adjustments and reductions

	Cost reduction for max reduction scenario	**Cost reduction for realistic scenario**
Schedule change	1.3%	0.7%
Potential improvement	8.4%	7.6%

2.3.4 Limitations

The limitations of this study, which made it difficult to implement was mostly human based. The human factors make difficult what seems on paper to be beneficial to a mine. The reductions also include improvement on all energy consumers found at the mine. This, again, looks good on paper but is not feasible in practice as typical energy saving companies have limited resources to accomplish this task. They would rather focus on implementing and maintaining energy management solutions on the largest systems (such as compressed air systems).

2.4 DISCUSSION

The results show the potential for cost reductions on the mine based purely on the TOU tariffs. Existing operations at the mine cause some utilities' power demands to increase during peak TOU tariff times. This increase could mainly be attributed to the compressors at the mine. High power demands were found during morning and evening peak TOU tariff time ranges during the winter and summer.

Regarding the TOU tariffs, it was found that moving the shifts of the different shafts to a more appropriate time had positive effects. The ideal was, however, to align the schedules to the times on the mine when the power demand was the lowest. The low utility power demand times correlated with the air demand, and the compressors were found to be the most important and most significant energy consumers. The compressor power demand was related to the air pressure requirement. The air pressure requirement was, in turn, connected to the mining operational schedule.

When the schedules from different sub-systems or shafts were aligned, the effect of the peak TOU tariffs was maximised. The maximum cost reduction scenario indicated that the maximum cost reduction occurred where the two shafts' blasting shifts were aligned. The blasting shift is a time when there is little other activity on a mine, as it is dangerous for personnel to be underground. This means that all systems experiencing a power demand minimum during this time would be affected by the schedule change. The same is true for the end of an evening shift when personnel are exiting the mine. Consequently, there is a gap between the evening shift and the next drilling shift. Initially, the schedules of the two shafts on the ring varied considerably. Shaft 7 underwent a blasting shift from 13:00 to 15:00, whereas Shaft 1 had a blasting shift from 17:00 to 19:00; that is a four-hour difference.

The realistic scenario proposed a schedule change that was more realistic and possible to implement. The power demand reductions that were estimated were not definitive. These reductions were dependent on the simulation of multiple energy efficiency projects leading to previously mentioned improvements found from literature. This study, therefore, shows the potential implications of integrated load management and operational schedule optimisation on the utility power demand and cost savings at deep-level mines on surface and underground. Chatterjee *et al.* showed the effect of mining schedules on ventilation demand [15] and studied integrated ventilation fan usage. Badenhorst *et al.* studied the effect of downtime and changed schedules in rock hoist optimisation [44], including integration with DSM. Peach *et al.* and Booysen *et al.* respectively showed improvements in control philosophies in refrigeration [73] and compressed air systems [68]. This study went further by holistically analysing a mine regarding its utility power demand and operation schedule. The study combined the findings of existing research and described an analysis which included numerous mine utilities, as was individually discussed in several studies, some of which are discussed. An integrated load management solution was consequently proposed in this study, which included all the energy-consuming utilities on a typical platinum mine. Reductions in all the utility power demands could thus be affected by simulating different operational improvement projects on the mining system as indicated in the studies described in the literature review. Now that cost reductions were shown to be possible through the study, practical application would be the next step in reducing power demand at the mine.

The compressors supplying compressed air to the case-study platinum mine were found to be the most significant utility at said mine regarding power demand, as they consumed up to 55% of the total energy supplied to the mining system. Compressor demand during non-drilling shift times mainly depended on the efficiency of air-use for mining purposes. During the blasting shift, the air demand was dependent on the extent to which air consumption can be reduced across the shafts. Compressor control can only be adjusted or improved based on the shafts' demand. The study reported on in Article 2 built on these findings, with the determination of a method with regards to a compressor's power demand and air supply to calculate its performance and characterise the system. This utility was the compressed air system.

The primary objective of Article 1 was to analyse mine utilities by peak TOU times holistically considering the operation schedules of each shaft on the system and the interconnectedness between shafts and systems. The prior study showed that analysis of relevant power demanding utilities in combination with mining operations could lead to power demand reductions.

CHAPTER 3 SIMPLIFIED METRIC TO CHARACTERISE AND EVALUATE COMPRESSED AIR SYSTEMS ON PLATINUM MINES IN SOUTH AFRICA


[12]

The previous chapter highlighted the need for methods to analyse compressed air usage patterns based on utility power demand. This chapter consequently describes a simplified method for doing so using specific energy as a metric. The resulting method was used to characterise a compressed air system before and after improvements on the control and instrumentation side of the compressors were implemented and was successfully implemented in its purpose.

[12] W.G. Shaw, 'Compressor at South African platinum mine,' Personal photograph, South Africa, 2018.

3.1 PREAMBLE

From Article 1 and through the analysis of mine utility power demand, it was found that compressors were a significant power-demanding utility on a platinum mine, consuming up to 55% of the supplied energy. To further investigate mine energy management, compressors as a utility was studied. Compressors have variable energy usage, which follows the demand from mining personnel working underground (mining operations schedule), as indicated in Chapter 2. The compressed air system (CAS) was found to be a significant power demanding utility, and a second study reported on in Article 2 here, was conducted, focusing on the performance of these systems. A literature review was conducted to formulate a research objective for this study.

The purpose of this chapter is to summarise the literature review of the second article as well as to underline critical research that led to the study problem and objective. The research focused on compressors, CASs and the energy use performance of the compressors and system.

3.2 LITERATURE REVIEW

CASs vary in size and are complex in their setup, as indicated by Schutte *et al.* and Mousavi *et al.*, where different types of compressors (centrifugal [74] and rotary [75] compressors) in different configurations were required to meet differing compressed air demands [74], [75]. However, CASs are typically energy intensive [76] and inefficient [77]. These systems comprise two major components, namely the compressed air supply (compressors) and the compressed air demand (end users using compressed air) [78], which are connected through a compressed air network of pipes [78]. There are various inefficiencies in such networks, and it has been found that typically only 10–30% of compressed air reaches end users [75]. The system further consists of compressors with different purposes, such as baseload and trimming [28]. Baseload compressors operate during lower air-demand times and are relied on to supply the baseload compressed air to the mining system [28]. Trimming compressors are used to account for fluctuations in air-demand in the mining system [28].

Inefficiencies and performance decreasing factors are usually present on both the demand and supply sides of a CAS [74], [76]. The supply side typically consists of multiple compressors, whereas factors affecting the supply side include, but are not limited to, control strategies, compressor configuration and compressor pressure set-point controls [74], [78]. Demand-side inefficiencies usually consist of poor usage and compressed air maintenance among compressed air users, with leaks being a significant feature [74], [78]. Furthermore, there are substantial differences in pressure demand between end users, requiring both high and low pressure on the same compressed air network [74]. It is therefore difficult to analyse such a system entirely without in-depth knowledge thereof [76]. In their study regarding CAS energy efficiency, Mousavi *et al.* highlighted the importance of understanding the system and compressors regarding system performance and efficiency [75].

Various methods for analysing CASs have been reported in the literature. However, each has a particular set of advantages and difficulties. Seslija *et al.* described a systematic approach where the process starts with an audit and system analysis [76]. One difficulty that may arise during audits on complex systems is the time- and cost-intensiveness. Jiang *et al.* described an analytical model that was developed from first principles to predict compressor performance based on geometric information [79]. This method takes into account different parameters that may not always be readily determined in actual systems as well as characteristic curve studies that may be difficult to implement as changes are made on the system [79]. Friden *et al.* used a model built in Simulink from the Compressed Air Model Library, which uses an audit of air usage patterns and user-defined requirements [80]. The model generates system configurations with alternative equipment and computes the predicted life cycle cost [80]. It also selects the configuration that meets the specifications and leads to the lowest life-cycle cost [80]. The model is, however, complex and requires an audit, which is likely to be time-consuming and difficult. Paraszczak focused on how to understand and assess mining equipment regarding different factors, such as availability, equipment utilisation and production efficiency [81]. This author used a mathematical model, considering the aforementioned factors, to understand and assess mining equipment effectiveness. However, the difficulty of this method pertains to the factors mentioned not necessarily being measured or known. The method also does not explicitly focus on a CAS but can be applied to specific components thereof.

Therefore, understanding the performance of complex CASs is difficult and time-consuming. Nonetheless, Mousavi *et al.* made use of the specific energy metric (simplified metric) as a performance indicator and to grade compressors. They found that the use of this metric led them to use more efficient compressors to meet the air demand better [71]. Therefore, it may be possible to use specific energy as a simplified metric to determine the performance of a complex compressed air system where limited data are available. Giacone and Mancò showed the use of specific energy in their study on energy efficiency in industrial processes [82]. These authors found that specific energy was useful in measuring a system's performance, but that it was also necessary to add other metrics in their specific case. Benedetti found that energy measuring, controlling, budgeting and forecasting were rarely performed for compressed air production [83]. The study shows the need for a simplified method to measure compressor performance as this would indicate fluctuations in all the above mentioned. Furthermore, Ganjehkaviri *et al.* found that as the efficiency of compressors increased, exergy efficiency increased accordingly, but so did total cost [84].

Mousavi *et al.* exemplified the use of specific energy in the analysis of a compressor combination to determine the combination that best suited the compressed air demand [75]. These authors, therefore, used specific energy metric as a key performance indicator but did not use it to analyse CAS performance throughout daily operation. Afkhami *et al*. showed the use of different forms of specific energy to compare power saving actions in a cement production plant [85]. Their study analysed the energy efficiency of CASs and investigated different compressor configurations and the use of different settings to predict the power demand of the system [75]. Afkhami *et al*.'s method firstly determined the compressor priority, after which the effects of changing the maximum capacity of the compressor supplying base load was analysed [85]. Paraszczak [81] also identified the need for a simplified method to determine system performance under time constraints. Current methods, which are complex and time-consuming, typically use simulations [86], audits [76] and analytical models [87] to evaluate CAS performance methods.

In summary, the literature review revealed that there is a need for a simplified method to analyse a complex CAS throughout daily system operation and measure the performance of such a system. The method must apply to any mining CAS.

3.2.1 Article 2 study research problem and objective

From the first study and throughout literature the problem of complex compressor performance strategies persisted. There is a need for a simplified method to characterise compressed air system performance using specific energy as a metric, during normal system operation.

The objective of the study reported on in Article 2 was to determine whether a simplified method, using specific energy as a metric, can be used to characterise and evaluate the performance of complex South African platinum mine CASs. Specific energy was tested as a simplified metric to measure the performance of the supply side of a CAS throughout the daily system operation. The appropriateness of specific energy as a metric for analysing CAS performance was tested by evaluating the performance of the CAS regarding specific energy before and after optimisation projects were implemented.

3.3 ARTICLE DESCRIPTION

3.3.1 Introduction

The objective of the study described here was to formulate a simplified method that could be used to characterise a complex CAS. The article written to report on this study was published in *Sustainable Energy Technologies and Assessments*. The article, titled 'Using specific energy as a metric to characterise compressor system performance', can be found in its entirety in Appendix B. The following section comprises a brief description of the methods and a discussion on the essential findings of the study. The success of the method depended on whether it could be used to characterise a CAS before and after performance-increasing initiatives were implemented.

The case-study CAS was a large, complex system consisting of nine compressors with a total rated energy consumption of 34.7 MWh and an average total actual energy consumption of 24 MWh. The rated compressor power demand varies from 1 to 5.1 MW, and the compressed air supply ranges from 10000 to 56000 m^3/h. The system consists of approximately 10 km of piping from the supply (compressors) to the demand (underground shafts). The focus of this study was on the supply side

3.3.2 Summary of methods

The metric used in this study was specific energy (*SE*), described by Equation 1. The metric *SE* uses the rated utility energy consumption (P), of the compressor or system, and the supply flow (f), or system demand at said energy consumption. The compressor supply flow is dependent on the demand of the system, which is, in turn, dependent on the mining operations, including mining personnel working underground and using compressed air. Initially, the system compressors were analysed to determine an ideal system baseline consisting of the rated specifics of the compressors in the system to calculate the ideal *SE* at each time interval.

$$\boldsymbol{SE = \frac{P}{f}} \qquad \textbf{Equation 1}$$

The unit of the demand flow was kept as m^3/h instead of kg/s as this is what was normally measured on the case study mine using compressed air volume flowmeters. The unit (m^3/h) would also be better understood by mine personnel as it is what is normally used. Multiplying Wh/m^3 with 0.77 (at reference temperature of 0 °C and a pressure of 101.35 kPa) changes the unit to Wh/kg where the flow will then be measured in kg/h. The calculations for specific energy found in literature [75] used m^3 instead of kg.

The actual system operation was then determined using historical data logged by the mine supervisory control and data acquisition system. The data were filtered to exclude all abnormal situations, which develop when compressors start up, shut down and trip. Filtering was firstly performed to minimise the effect of data loss and irregularities. Secondly, it was done to filter out the effects of the previously described abnormal situations, which can either lead to a consistently higher or lower *SE* value than that during normal weekday operation. As the average normal operation was taken, irregular data would skew the perception of normal operation. Average normal operation also led to a better comparison to validate improvement. Microsoft Excel with an Office 365 subscription was used for data analysis and filtering. Data loss or irregularities include the following:

- Values fluctuating from normal operation to 0 from a specific time interval to the next,
- Data flatlining at a specific value,
- Data limiting out and flatlining and
- Compressor energy consumption is exceeding the measurement range of the rated and possible minimum energy usage of the compressor, which leads to irregular *SE* value (extremely high or low when considering the normal operation of the said compressor).

Data irregularities caused by compressor operation include the following:

- Blow-off initiated during start-up and shutdown, leading to supply flow being much lower than energy consumption and
- *SE* value that is outside of the normal operation range, being either too high or too low compared to the rated specifications and the normal compressor operation.

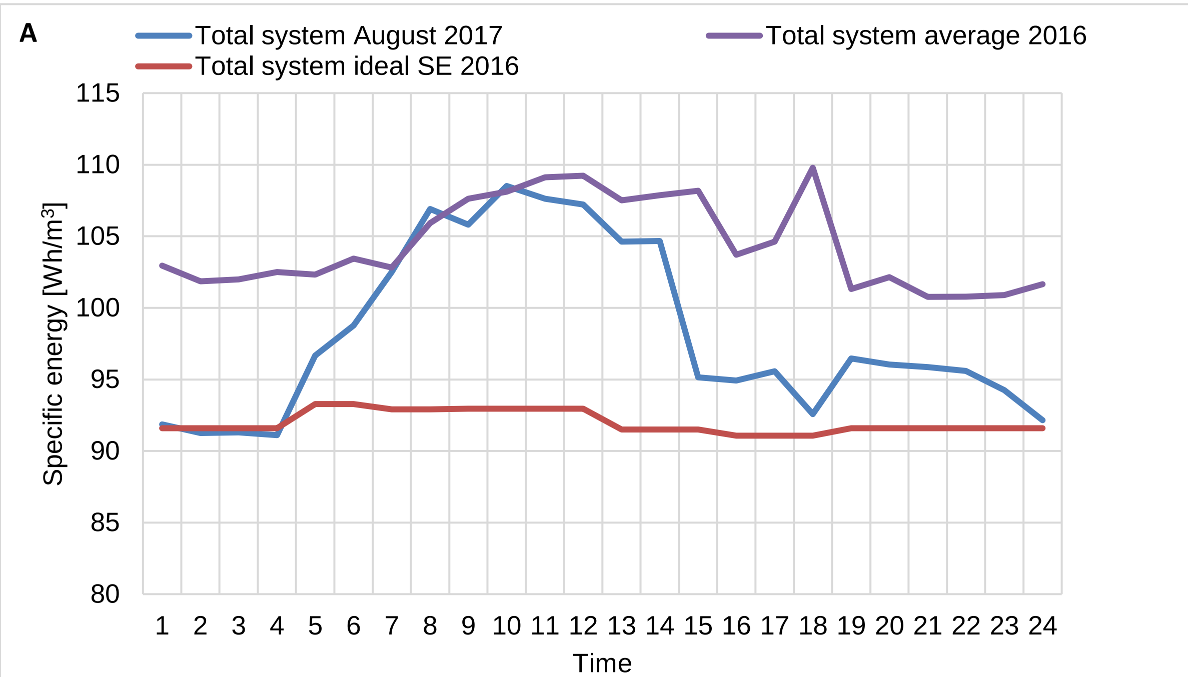
The resulting data is relevant as it explains the average normal operation of the compressor for example, when the compressor is normally always on. The system data were then analysed to isolate and prioritise compressors operating inefficiently. Finally, a specific scoring philosophy was used to distinguish between compressors operating within a practical range and compressors operating outside of that range and needing attention.

The method was validated by comparing the specific energy of the system before and after improvement projects were implemented on the system. The results were analysed, and conclusions were drawn regarding the sufficiency of the method.

3.3.3 Summary of results

Numerous improvement projects were implemented on the system. These improvements included lowering the master pressure set-point, improving compressor control, improving compressor scheduling (start-up and shutdown sequence) of trimming compressors and improving instrument air of the baseload compressors. The performance of the CAS was determined before and after project implementation using specific energy as a metric and implementing it in conjunction with a simplified method of analysis.

Figure 11A illustrates an improvement of 6.2% in the overall system based on specific energy. The average specific energy decreased from 104.5 to 98.2 Wh/m^3 before and after the improvement projects were implemented. The baseload compressors improved with an average of 3% using the proposed method for characterising the compressors. Figure 11A shows a reduction in specific energy during off-peak periods, but this is not carried over to the drilling shift, where the specific energy remained relatively constant. As shown in Figure 11B, when comparing the energy consumption and corresponding supply flows, there was a decrease in power demand during off-peak periods, whereas the supply flow remained constant.



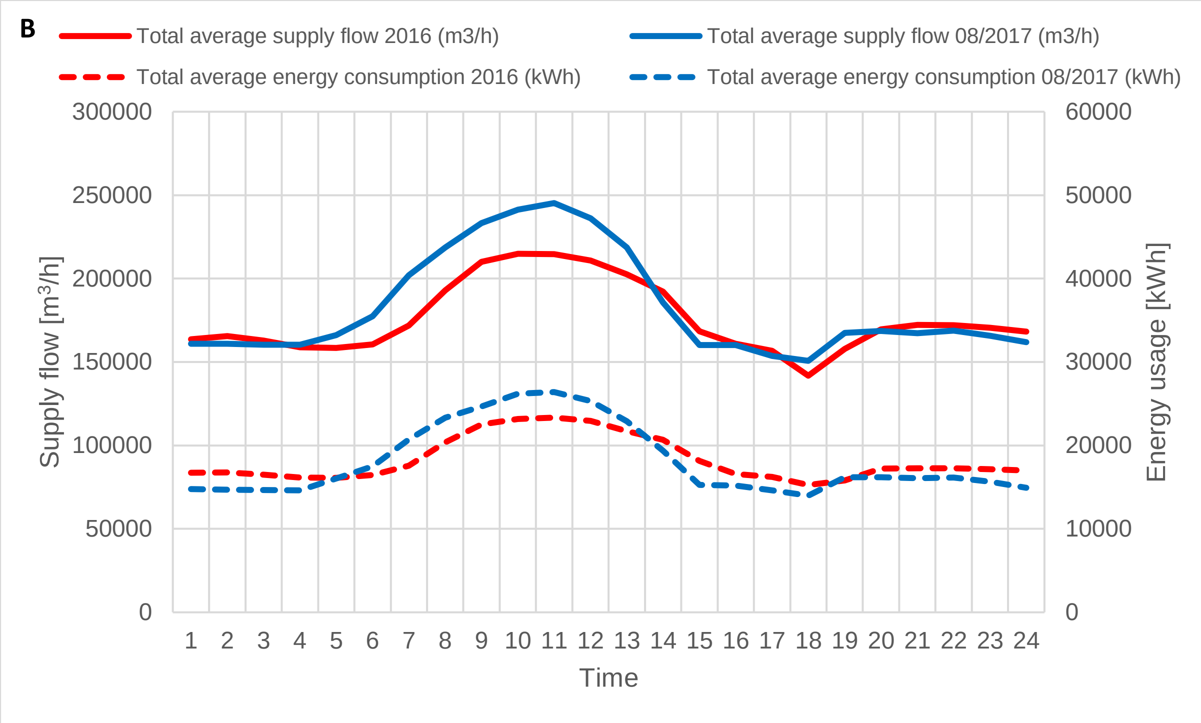


Figure 11: (A) Comparison of total system specific energy (SE), and (B) comparison of total system energy consumption and supply flow in the compressed air system of the studied platinum mine

A measurement and verification approach were used as a comparison to the results found using the method described in the article. The utility energy consumption during and outside of the drilling shift was compared before and after the improvement projects were implemented as illustrated in Figure 11B. The supplied compressed air flow was compared in the same fashion.

The average energy consumption outside the drilling shift was reduced by 7.8%, with the supplied flow only being reduced by 0.4%. The average specific energy outside the drilling shift decreased by 8.8%. This shows that the power demand decreased substantially, but the efficiency with which energy was used to supply compressed air increased as the supplied flow remained virtually constant on average. The average power demand in the drilling shift increased by 9.2%, with the supplied flow increasing by 10.1%, which can be compared to the average specific energy in the drilling shift decreasing by 1.2%. This again indicates that, although more energy was used, the increase in the supplied compressed air was more, which implies that the efficiency with which air was generated improved. As previously described, the combination of these factors led to a decrease in specific energy of 6.2% (Figure 11A).

3.4 DISCUSSION

Specific energy has not previously been used as a metric for investigating and tracking compressor performance in mining operations [75]. It was found to be a sufficient indicator of compressor performance and can track performance increases or decreases as a project is being implemented. The method used in this study was applied to a large complex CAS of a platinum mine because of the limited data required. A basic understanding of the system was nonetheless necessary before the method could be applied. As shown in this study, the method can be used to track the performance of a CAS. It is, therefore, time-efficient to apply it to the system, as the data used are typically available and comprises essential variables in the system. It must be noted that the correct interpretation of the data is essential to ensure accurate decision making.

During the review of specific studies discussed in the literature review, the new simplified method discussed in Article 2 could have been used to improve the decisions made in various studies in literature. This simplified method can increase knowledge of the CAS and complement existing performance characterisation studies by Jiang *et al.* [79] and Saidur *et al.* [77]. In the case of Jiang *et al.*, the simplified method could have provided additional information when characterising CASs. In that of Saidur *et al.*, the method may have improved the analysis process and added additional knowledge when the effects of improvement projects on CASs were analysed. The simplified method could further be used to track compressors' performance using different control modes [86], [88] and to measure performance during different compressor schedules [89] and configurations [90].

Saidur *et al.* stated that a variable speed drive on the driving motor of a compressor could potentially save power and improve compressor efficiency [77]. This could be beneficial, as this study showed that the compressors at the studied mine operated at full load for only a part of the day. The simplified metric (specific energy) could be efficiently used to characterise and analyse the CAS performance before and after the abovementioned initiatives were implemented, simplifying the analysis process. A compressor's operating point changes according to the specific control strategy, such as inlet guide vane control, suction throttling, discharge throttling, motor speed adjustment and flow recycling [88]. Control modes for small reciprocating and rotary compressors include start/stop, load/unload, inlet modulation, auto-dual, variable displacement and variable speed control [86]. These methods would have changed the specific energy of a compressor, as both the energy consumption and supply change. For instance, in a study by Jovanovic *et al.*, less flow from each compressor was necessary to fill the reservoir [87]. This meant that compressors were utilised more efficiently to increase the pressure. The specific energy metric could thus have been used in the above studies to analyse system performance and the applied methods efficiently.

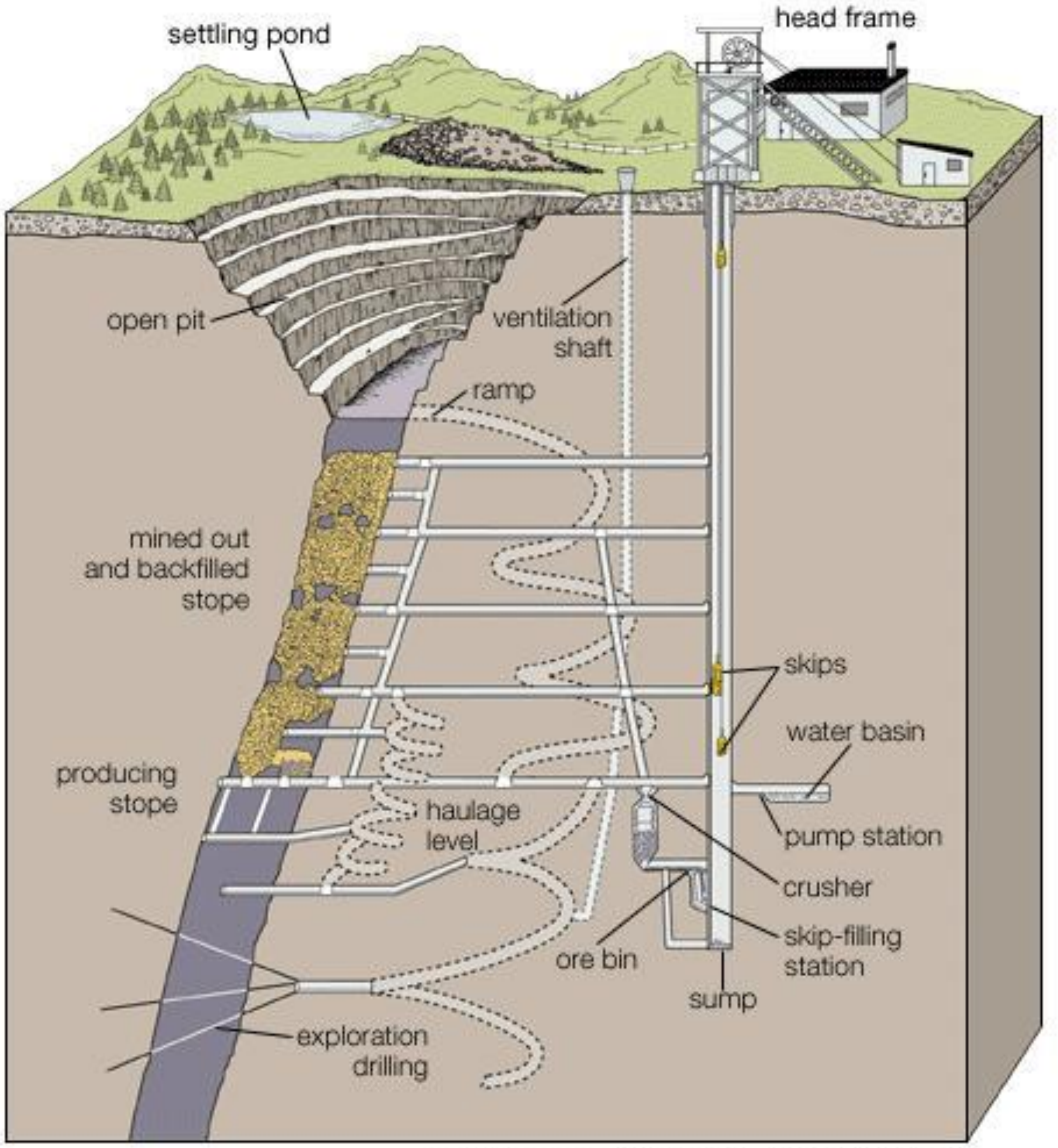
The specific energy metric could further have been practically applied to analyse the discussed control modes in real time and thus isolate problems in the system or control mode, as the metric considers the supply and power consumption of the compressor. It could be beneficial to use specific energy to prioritise and control a CAS automatically, and it could prioritise the necessary compressor during a specific time for a specific air demand. Al-Busaidi and Pilidis investigated the effects of compressor shutdown and maintenance on the polytropic efficiency of each stage [91]. It was found that efficiency usually decreased substantially after a maintenance shutdown due to build-up on the compressor blades [91]. The specific energy metric could have been used in this case as an efficiency monitoring tool to obtain a clear indication, when used in a day-to-day time frame, of the performance variance of a compressor.

It was also found that a reasonable estimate for an ideal specific energy value of a compressor on the studied mine was approximately 90–91 Wh/m^3. This value was, however, not always applicable, and it could only be chosen after analysis of both the supplied airflow and power demand of a compressor. In cases where the normal operation of the compressors cannot be determined from analysis or where it was not feasible because the operation changed too much, it may be considered as good practise to calculate and plot the ideal specific energy for each possible state of the system.

The proposed new method was applied to a complex CAS in the studied platinum mine to determine the current performance status of the system. The results showed that the simplified metric was successful in indicating scope for CAS performance improvement and monitoring the impact of improvement projects implementation. Further research is necessary to determine whether the proposed method could be successfully applied to other types of CAS. The simplicity of the metric, however, suggests that the method may work efficiently to characterise complex systems.

The study fulfilled the study objective regarding the specific analysis of mine power management and the corresponding formulation of a simplified method to characterise compressor system performance. The research problem was addressed in the study.

CHAPTER 4 CONCLUSION



[13]

This chapter briefly summarises how the study objectives were reached and the contributions that Articles 1 and 2 showed to addressing the objectives. The shortcomings of the current study and recommendations for future work are also made, after which a summary of the novel contributions of the study is provided.

[13] H. Hamrin, 'Guide to Underground Mining Methods and Applications', *Atlas Copco*, Stockholm, 1997.

4.1 CONCLUSION

This article-based dissertation aimed to analyse mine power management considering utility demand. The study adopted a holistic and specific look at utility demands and the dependence of these demands on mining operations at a South African platinum mine. To initiate efficient mine power management, the entirety of utility demands and the variability thereof according to the mining operation schedule should be considered, as indicated in the first article. This was more done explicitly in the second study, where the focus was placed on the compressed air system. The dissertation, therefore, fulfilled both research objectives by analysing mining systems to holistic mine energy management using an integrated load management approach in Article 1 (Appendix A) and characterising a compressed air system using specific energy as a metric in Article 2 (Appendix B).

4.2 SHORTCOMINGS AND FUTURE WORK

Shortcomings of this study include that Article 1 does not recommend practical implementations and only reports on a theoretical analysis of the solution to the problem. The study also has limitations in that the human factor was not thoroughly analysed. The human factor may be the determining factor in any such under. The study only included a concept of holistic energy management and not actual results of adjusting the schedule and implementing power demand reductions.

The methods of the study reported on in Article 2 were only validated by mining compressed air systems and not by other systems, such as plant compressed air systems. The method could have also led to a more thorough analysis if used during normal daily operation whereas the average for a specified time period was taken to compare.

Another shortcoming of this study is that the methods were not applied to other types of mines. This includes gold mines, coal mines and so forth. Although the basic operation at these mines are like platinum mines there are some major differences as well. The refrigeration systems at gold mines are typically much larger in terms of energy consumption.

There is a need to practically implement the concept of integrating load management and holistically analysing mining system’s power demand, proposed in Article 1. A generic method may also be investigated that could be applied to any mining system, which could result in the best possible schedule for various sub-systems and potential utility power demand reductions. The pressure requirements of mining sub-systems are dependent on specific components being used for specific tasks. An in-depth analysis of these components may lead to valuable insights.

Furthermore, since compressors are one of the primary energy consuming utilities on a typical mine, there is a need to analyse the mining operation system further to improve and potentially automate control using the method described in Article 2 as a foundation. Specific energy can be used as a metric to drive the automated control of compressors, and this may be a valuable topic to study. There is a further need for analysing the mining operation system regarding high-pressure components. These components drive the compressor demand and thus increases the utility power demand.

4.3 NOVEL CONTRIBUTIONS

The novel contributions of this article-based dissertation are described in this section. As shown in Chapters 2 and 3, each article consists of a research objective that addresses a persistent problem found in literature, namely to holistically analyse the variable utility demand with regards to TOU times and the interconnection between different utilities while also considering mine operation schedules in Article 1. The objective of Article 2 was to characterise compressed air systems, as a high energy consuming utility, regarding its performance.

This study, therefore, contributes to improved methods for (1) analysing a mining operation system according to TOU tariffs and (2) for characterising a specific major power consumer, namely compressors.

4.3.1 Article 1

This study involved the holistic analysis of a platinum mining operation system considering time-of-use tariffs and proposed schedule adjustments to this system to enable cost reductions and schedule alignments of multiple shafts or sub-systems. This study addresses the need identified in the literature review for a holistic analysis of a mining operation system considering TOU tariffs. The simulation of potential adjustments resulted in a suitable, realistic schedule adjustment.

The first article reported on a holistic analysis of a mining operation system regarding integrated load management. The system was analysed with particular regard to TOU tariffs, and the operational schedules of all sub-systems were therefore considered. The dependence of power demanding utilities on the operational schedules was also analysed.

The findings of the study can be summarised as follows: significant cost reductions were found when adjusting operation schedules to consider differing tariff costs. The adjusted schedules allowed further power demand reductions to be simulated. The reductions were possible as the shaft schedules on the mining system aligned. The combination of schedule adjustments to address the misalignment in shaft schedules and furthermore the simulation of power demand reductions led to significant cost reductions.

4.3.2 Article 2

This study contributed to an improved method that utilises a known metric (specific energy) to characterise a complex compressed air system (with few available data) regarding its performance. The metric is dependent on the utility and system demands of said utility. A need for a simplified method that uses specific energy as a metric to characterise compressor system performance was identified. The method and use of the metric were verified by analysing a complex compressor system before and after improvement initiatives were implemented on the system. The method applied to compressor systems and can also be applied to a specific individual compressor to in turn analyse the said compressor's operation.

In conclusion, this dissertation contributed to power demand reductions and operation improvement of the deep-level mining industry and specifically the platinum mines used as case studies. The implications of the study are firstly that significant cost reductions are possible when mining operation is improved together with the implementation of integrated load management strategies. The characterisation of critical utilities' performance, such as the compressors, regarding energy use, can inform better decision making to improve said performance and finally reduce utility power consumption. The electricity cost of mines will continue to increase as tariff costs in South Africa are predicted to increase egregiously in the foreseeable future.

CHAPTER 5 REFERENCES

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APPENDIX A. HOLISTIC ANALYSIS OF THE EFFECT ON ELECTRICITY COST WHEN VARYING SHIFT SCHEDULES ACCORDING TO TIME-OF-USE TARIFFS

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Holistic analysis of deep-level mine operation considering time-of-use tariffs

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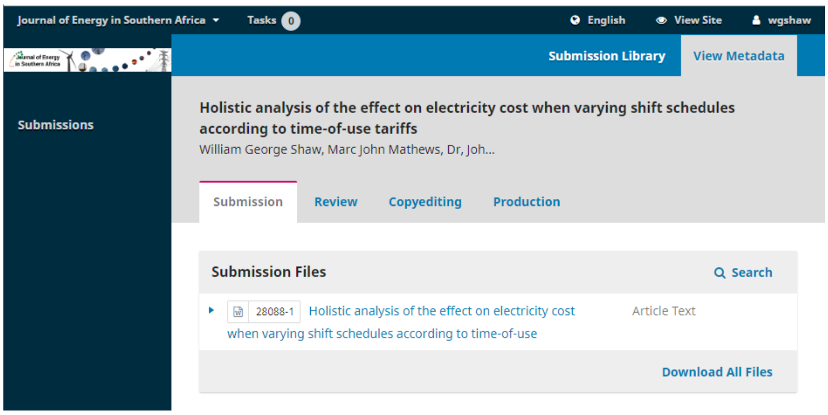

1 App. A.1: Article I

Holistic analysis of the effect on electricity cost when varying shift schedules according to time-of-use tariffs

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Abstract

In the past the cost of electricity was not a significant, therefore it was not common practice for mining companies to take peak time-of-use (TOU) tariffs into account for their shift schedules Throughout literature, no clear analysis was described which holistically analysed an entire mining system regarding power consumers, using a top-down approach. Therefore, the aim of this study was to analyse an entire mining system with the notion of integrating load management with shift changes. This was achieved by thoroughly analysing power consumers, mine operational schedules and their interconnectedness. The study illustrated the potential power reduction of a specified case study system. The power reduction was estimated statistically using existing studies and was applied to power consumers when specific periods at the shafts aligned. A specific mining system was analysed as a case study, and a maximum savings scenario was determined. The maximum savings scenario schedule change resulted in a 1.3% reduction. Also, system improvements had a potential reduction effect of 8.4% which was primarily contributed to a reduction in compressors power consumption. The implications (large adjustments of shaft operation and shifts starting at difficult times) of the proposed schedule adjustments necessitated a realistic scenario. The realistic scenario had a financial reduction of 0.7% to effect. The realistic schedule change, however, opened the door for large system operational improvements. When the operational improvements were simulated on the relevant power consumers, the effect was a potential reduction of 7.6%.

Keywords: schedule adjustment; time-of-use; cost reduction; deep-level mine; integrated load management

Introduction

The mining industry is under financial pressure due to factors such as the cost of electricity, which has not been a problem in the past and thus was not in the spotlight from a mining perspective. Thus, the need arises to save energy and reduce electricity costs. With input costs having increased continuously while the precious metal costs decrease, it has become more common for mining shafts to close operations and be cleared by contractors [1]. This has also led to an increase in tensions as unemployment and poverty have also, subsequently, risen [1]. However, the low hanging fruit has already been implemented. Energy reduction projects have been ongoing from the late 2000s [2]. With the South African energy crisis of 2008, these projects started to pick up speed. [3], [4]. A dramatic increase in electricity tariffs was also seen during the year of 2008, as illustrated by Bohlmann and Inglesi-lotz [4].

Van der Zee found that at a typical South African underground platinum mine, electricity costs are approximately 24% of the total expenditure of the mine as of 2015 [5]. This 24% can further be divided into summer and winter use. The cost of electricity during summertime peak TOU was found to be approximately 30% of the total daytime electricity costs. Winter tariffs led to a staggering 50% of the total daytime electricity costs spent during peak TOU. However, the peak TOU hours only constitute 20% of the entire day.

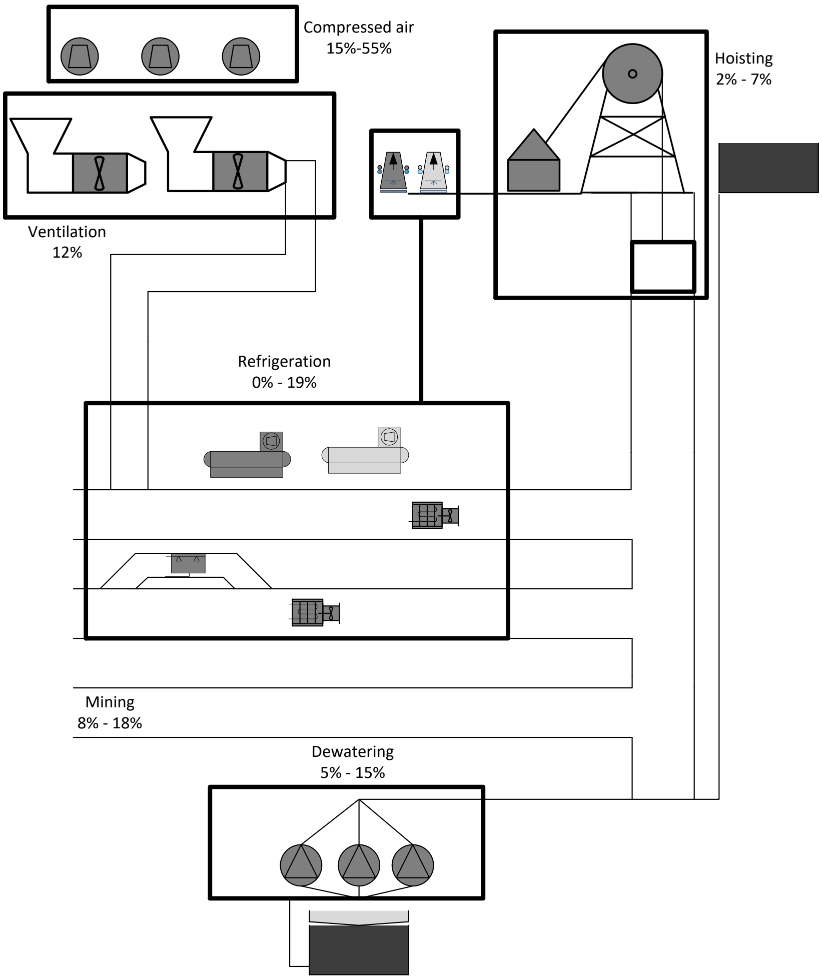


Figure 1: Typical electrical systems present on platinum and gold mines with the relative percentage of total power usage [6].

Further variation in the energy profile occurs throughout a normal operational day as the different systems, shown in Figure 1, are switched on and off and ramped up and down depending on the requirements underground. This is, mainly because of the different shifts and schedules used to facilitate underground mining [7]. The result is that some power consumers are utilised more during certain times of the day or certain shifts. During the drilling shift for instance, compressed air is utilised fully and thus compressors are run at maximum power [7]. The ventilation fans are utilised throughout the day for ventilation to underground and to extract dangerous gasses from the mine after the blasting shift [7]. The winders are utilised when mining employees need to be transported up and down the shaft and for removing ore from below ground, thus winder utilisation usually occurs maximally before and after drilling, afternoon and night shifts [7]. Compressed air is again utilised to a degree during the night shift when loaders are used to load ore and waste onto locomotives. Pumping systems are used whenever the dams at the bottom of the shaft reach specific levels [7].

The prevalence of these changes in energy usage because of the different shifts has provided the opportunity for energy cost savings projects which take advantage of the TOU tariffs by shifting load to different times as illustrate by Storm, Gouws and Grobler on an irrigation pumping system [8], and Mohamed and Tariq who reviewed different load management strategies [9]. Table 1 summarises the state of the art regarding load shift implementation in the South African mining industry. A load shift requires the energy and operations of a specific electricity consumer to be reduced during peak TOU tariffs [10]. In addition to load shifts, improved control philosophies were found throughout literature to be one of the methods with which energy usage was reduced on mines. The use of improved control philosophies as an energy-saving initiative is also indicated in Table 1 and an example can be seen in a study by Liebenberg, Velleman and Booysen [11].

It can also be stated from practical experience that the schedules of shafts differ on the same system [12]. The schedules of shafts do not always make it possible to decrease the energy consumption during peak TOU times. The differing schedules cause difficulties when implementing improvement projects. Misalignment between the schedules of shafts causes difficulty when improving the control philosophy of a specific component. This is especially so when the component supplies to multiple users [13].

Table 1 indicates the current state-of-the-art regarding mine energy reduction projects. The shortcomings illustrated are from the systems that were analysed regarding energy reduction and operational improvement projects. Table 1 also indicates the typical consumption reductions found.

Table 1: Literature review shortcomings and typical power consumption reductions found

Studies	Component (no schedule change)									Integrated mining system and schedule change
	Pumping	Ventilation fans	Shuttle cars	Compressors	Rock winders	Loco battery chargers	Mine refrigeration systems	Jaw crushers	Conveying systems	
[14]–[21]	X									
[7], [22]–[25]		X								
[26]–[28]							X			
[29]–[31]					X					
[32]						X				
[33], [34]									X	

[35]								X		[redacted]
[36]–[40]				X						[redacted]
[41]			X							[redacted]
Typical load reduction [%]	50%	40%	-	25%	57.5	46%	45%	34%	10%	[redacted]

Power reduction projects were only implemented on isolated systems without adjusting operational schedules [7], [11], [16], [22], [31]. It thus becomes clear from the literature that previous studies have worked around mine schedules. This working around mine schedules is also indicated in Table 1. Systems are isolated but the integrated system, with all its underlying components, is not analysed in the existing literature. The schedules are also adhered to in existing literature. There are no existing studies that integrate load management and mine operational schedules or shifts.

Further indicated by the literature shown in Table 1 is that different energy consumers are dependent on different shifts in a mining environment. This is illustrated by Chatterjee *et al.* [7], Badenhorst *et al.* [31] and Peach *et al.* [42]. Chatterjee *et al.* illustrated the dependency on shifts by analysing the different processes in the mining cycle according to the ventilation airflow necessary as part of their model [7]. The study by Badenhorst *et al.* also illustrates the dependence of winder operation and thus power consumption on the mine schedule [31]. Peach *et al.* illustrates the dependency of a mine refrigeration system on the schedule of mining operations [42]. The analysis of the previous studies led to the formulation of the problem.

The primary purpose of this study is to analyse an entire mining system with regards to integrated load management (with all underlying shafts and decline shafts). The analysis must be done on an entire mining system to illustrate the possibility and effect of integrated load management on the energy usage of a mine. Integration implies that the dependency of the power consumers on the mining schedules must also be analysed. The final effect of the theoretically integrated load management must be evaluated.

Methodology

Overview

The following section presents an improved analysis strategy for solving the problem described in the previous section. The analysis took different constraints of a mine into account. The schedule for the different shafts on a system was then optimised to be able to decrease power consumption optimally. The power reduction was applied during specific times when the system allowed for it. An in-depth system and system constraint analysis were done. The system described is usually defined by the electricity network as well as the compressed air system.

System characterisation

System characterisation consisted of an in-depth analysis of the relevant power consumers on a mining systems' electricity network. The electric power distribution occurred within an extensive network, which also extends to underground reticulation. The first step of the analysis was to characterise the electricity network of a mine using a top-down method. The top-down method illustrates the interconnectedness between different parts of the network and how electricity was distributed. The top-down illustration led to a better understanding of the mining system as well as allowing the user to analyse specific mining system components.

An electricity network consists of multiple incomers from the primary electricity supplier. The incomers then feed the power to numerous feeders. Through the feeders, the electricity is finally distributed to the lowest level and the users. The users consist of various power consumers which are relevant to specific mining operations. These components can be described by, but are not limited to, the following groups (also illustrated in the literature):

- Compressors,
- ventilation fans,
- refrigeration systems,
- pumping systems,
- hoisting systems and
- conveying systems.

Operational analysis

Mining operations are usually related to a fixed schedule to which the mining personnel generally adhere. The schedule describes various shifts which represent actions that must be completed. These actions finally lead to the production of the necessary minerals or precious metals mined. Generally, the shifts at different mining shafts were found to be dependent. Where one shift describes a specific step of a process, the next shifts describe another action which is the next step in accomplishing the final purpose of the mine. This purpose is to produce raw ore which contains a particular mineral or precious metal.

As part of the new, improved analysis it was necessitated that an operational analysis is executed. A mining system may or may not consist of various sub-systems (or mining shafts). If the mining system comprises multiple shafts, the analysis describes the investigation of all the relevant shafts operations. Shafts are analysed when they could affect power consumption, as they may also affect the other sub-systems on the specific system. A shaft (sub-system) may also function as an individual system.

During the operational analysis, specific focus was placed on the pressure requirements of each shaft. The shaft pressure requirement was used as an indication of the intensity of the demand for services and thus a proxy for current production. The pressure requirement is applicable where compressed air is primarily utilised as a central service with which to mine [43]. The study stipulated that further analysis of the pressure requirement be needed. The need to determine the effects of the schedule and thus also the power alignment led to the need for further analysis of the pressure requirement.

Boyle’s law implies the similarity between the pressure requirement and the power demand. The law implies that if air is compressed to high pressure, it will likely be that the air is imparted at a high flow rate. Air at a high flow rate or pressure indicates that the energy content of the air is higher (more kinetic energy). Thus, air at a higher pressure requires more energy. As stated in the first law of thermodynamics, this implies that the energy consumption can be related to the pressure requirement. On a mine, the power demand can also be linked to the pressure requirement. Active periods in the mine usually requires higher pressures as compressed air is one of the primary services used. The need for higher pressure during active periods can also be seen from the graphs in the study by van Heerden *et al.*[43]. The study also illustrates the similarity between power demand and pressure profiles can be seen [43].

The operational analysis describes a vital step where each shaft operational breakdown is compared to the power consumption schedule of each user. The execution of the operational analysis led to the study of the dependencies and interdependencies of the power consumers.

Dependency analysis

Power consumers are either dependent on the various system operation schedules, or not. This dependency must, however, be analysed to gain an understanding of the multiple unrealised possibilities per the current operational schedule. A power consumer's degree of use and running status indicates the reliance of a specific power consumer on an operational schedule. The dependency of the power consumer was used during the evaluation phase of the analysis. It was also used to indicate how a specific component's power consumption changes with regards to the shafts schedule change, on which it is dependent.

A mining system comprises components which are utilised during normal operation throughout the day, such as ventilation fans [7]. The system also includes components that have varying degrees of power demand. Compressors and refrigeration systems are good examples of these, as they are dependent on the mining operation that is currently being executed [26], [36]. The power consumption of compressor and refrigeration systems has a distinguishable consistency regarding time-of-day and weekdays or weekends. There also exists components which have more random operational demands. These are not usually related to the mines operational schedule and do not stay consistent. These components include, but are not limited to, the various types of winders. The winders can also be prone to delays and scheduled inspections weekly and daily [29], [31].

Optimisation and evaluation

The following section defines the structure followed to determine potential optimisation. The structure includes the schedule adjustment as well as possible operational improvements. The evaluation of the optimisation is also discussed. The evaluation may lead to the reformulation of the schedule adjustment.

Operational adjustment

From the operational and dependency analysis, the flow of the study finally led to the investigation of possible optimisations or power reductions. The schedule adjustment proposal needs to consider all factors that are affected. It should also consider the financial implications of the adjustment. The proposed schedule adjustment must be of such a nature to align the different sub-system operation schedules. It should also take into consideration the peak TOU tariff times applied to the mine.

The schedule adjustment was used to align mine operations better for two reasons. Firstly, the reduction in power consumption and secondly, the improved alignment between shaft schedules which may potentially lead to further reductions. Alignment was the priority with the lower-order priority being to also decrease the power consumption during the morning and evening peak TOU periods.

Evaluation

The evaluation result was based on the feasibility of the specific proposal being implemented. Some constraints were analysed to verify the recommendation based on the ground of implementation. The following questions were asked to validate whether a schedule adjustment proposal was feasible:

1. Is the schedule adjustment of any one shaft too large, considering the production of the shaft? (2 hours on a shaft with more than 6000 tonnes production and 4 hours when the production is less than 6000 tonnes.)
2. Is the schedule adjustment of any one shaft unrealistic regarding the start and end times of a specific shift? (Changes in the middle of the night or an afternoon shift starting at 22:00.)
3. Is there a specific shift which does not "see daylight" at all?
4. Do the shifts of different shafts align enough to merit the change?

The results of the above questions can potentially lead to a re-analysis of the schedule of the mining sub-systems, after which an improved schedule adjustment proposal can be made.

Possible improvement simulation

An operational improvement analysis of the system and its lowest order components consisted of a statistical analysis where the power consumer's daily standard deviation was calculated. The standard deviation was compared to the average power consumption of the same consumer. The difference between the consumption outside drilling shift and the average power consumption minus the reduction percentage of the standard deviation was calculated. If the measured consumption was more, then the capability exists to simulate power reductions on the component

The potential analysis uses Equation 2.1 and 2.2.

$$\boldsymbol{P_{avg} - r_{reduct}\left(STD_{P_{pop}}\right) > P_i \;\therefore 1} \qquad \textbf{Equation 2.1}$$

$$\boldsymbol{P_{avg} - r_{reduct}\left(STD_{P_{pop}}\right) < P_i \;\therefore 0} \qquad \textbf{Equation 2.2}$$

Where P_{avg} is the average power on a normal weekday for a month, r_{reduct} is the reduction ratio found through literature and $STD_{P_{pop}}$ is the standard deviation of the power consumption average.

The new possible power consumption is calculated using Equation 2.3, which is an estimation of the improvement possible. The power reductions found in literature led to the formulation of Equation 2.3. A safety factor of 2 was used in this analysis, which is indicated by multiplying the reduction ratio by 50%.

The resulting power profile was then analysed to determine the financial cost reduction which may be possible with the simulation of the proposed energy reductions. The newly improved energy usage was determined for each component while considering the purpose of the component.

$$\boldsymbol{P_{new} = P_i - P_i\,(0.5 * r_{reduct})} \qquad \textbf{Equation 2.3}$$

Where P_{new} is the new, simulated, reduced power consumption of the component and P_i is the initial power consumption at a specific time interval.

Results and discussion

Overview

The following section illustrates the potential benefit which could be achieved by considering integrated load management on underground platinum mines. The theoretical analysis was applied to a South African Platinum mining company. The mine layout is represented in Figure 2, which illustrates all the relevant shafts relative to each other. The results of the study were used to prove the concept and demonstrate the potential of introducing proposed schedule changes. When considering only weekdays, the system has a total yearly power consumption cost of approximately ZAR160 million.

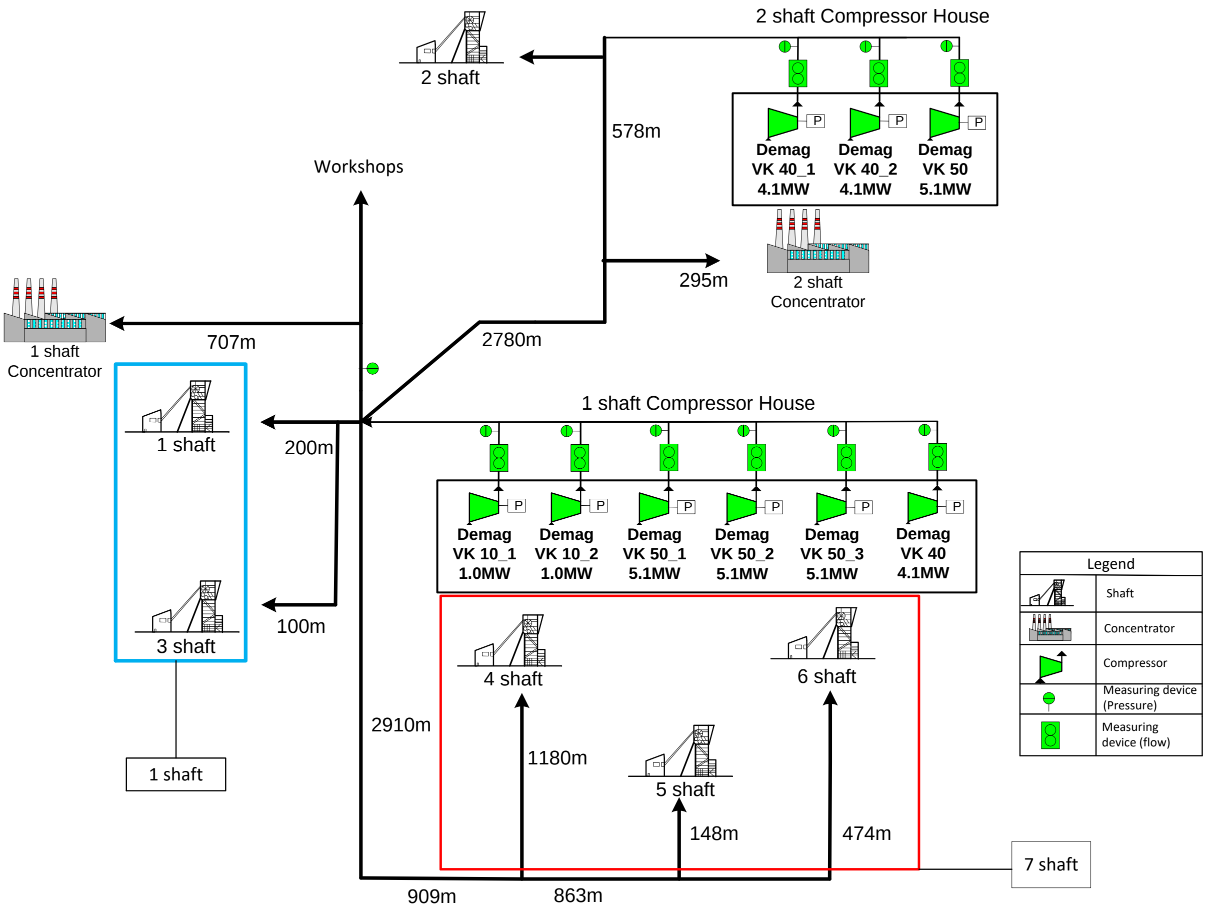


Figure 2: Mining layout

The system was characterised according to the electrical layout, which was used to isolate each power consumer. The electrical layout was used as a roadmap to apply the top-down method. During the study of this mine, 2 shaft was omitted. 2 shaft does not produce any ore and only consists of a concentrator which has a constant operational schedule and is therefore not applicable to this study. 1 shaft and 3 shaft are grouped under 1 shaft as both shafts have the same operational schedules. As 4 shaft, 5 shaft and 6 shaft all have the same operational schedules and work around the same mining operations; they were categorised as 7 shaft for simplification. The discussed combinations are also illustrated in Figure 1.

System characterisation and operational analysis

An analysis of the various schedules, as illustrated in Figure 2, was necessary as this was the only way the operational differences could be clearly understood. The different coloured blocks represent the different shifts, also described at the top of Figure 2, with the graph demonstrating the pressure profiles and the differences thereof. The pressure profiles clearly illustrate the different operational schedules. The pressure may be related to the power demand, as a reduction in pressure usually leads to a decrease in power consumption. A reduction in pressure also indicates less personnel working underground. A comparison of the two operational schedules of 1 shaft and 7 shaft illustrates the different times blasting shift (black block) occurs at the shafts. A lag in the schedule can also be seen during morning hours at 7 shaft.

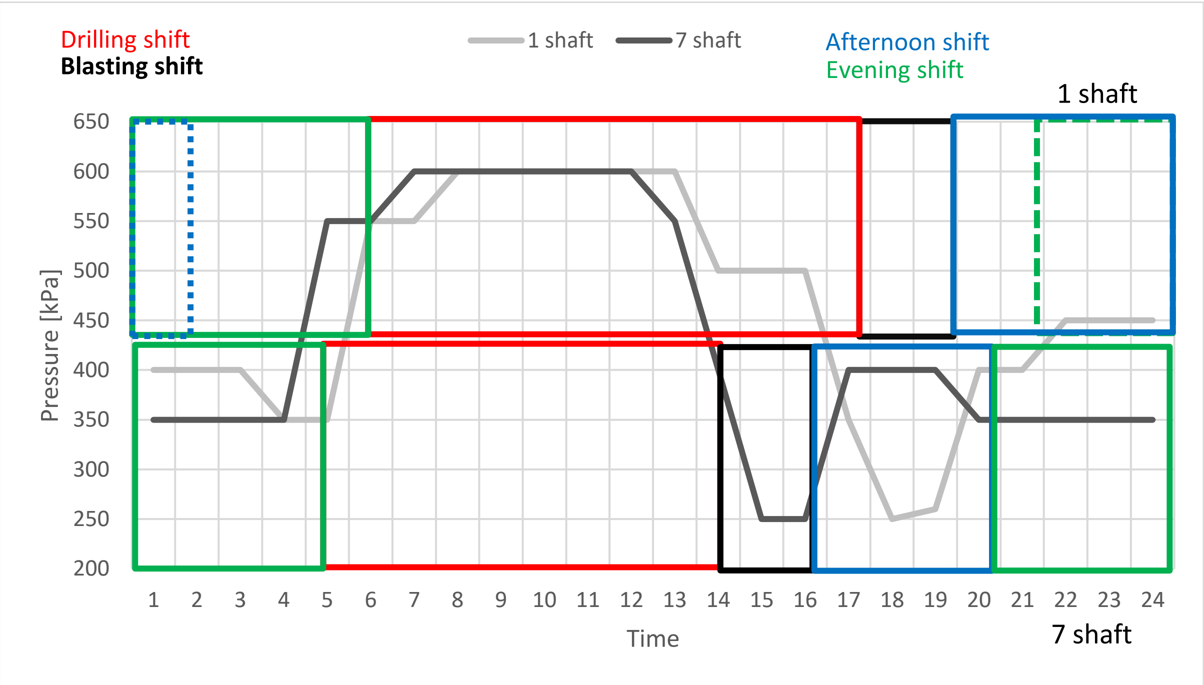


Figure 3: Mine sub-system operational analysis and pressure requirement

Figure 3 also illustrates the difference in the pressure demanded by each shaft during the afternoon and evening hours (14:00-19:00). 7 shaft reached a minimum required pressure first at 14:00. This is followed by 1 shaft reaching the minimum pressure requirement at 17:00, one hour after the 7 shaft blasting shift had ended. The difference in pressure requirement was also illustrated during the morning. 7 shaft drilling shift starts at 05:00 whereas 1 shaft drilling shift commences one hour later at 06:00. This time difference translates into a decrease in pressure by 200 kPa.

Operation adjustment

Preamble

The following section describes the schedule adjustments required at the relevant shafts to accomplish an improved schedule. The improved schedule further allows for enhanced operations concerning TOU tariff times. The schedule adjustment was made with two ideas in minds. Firstly, to achieve maximum financial cost reductions. Secondly, to heed a realistic new schedule which, the when applied, can potentially lead to further operational improvements and finally to financial savings.

Maximum-potential schedule adjustment

The first scenario that was analysed illustrated an example where, as described in the analysis strategy, the maximum potential financial reduction was simulated. The pressure requirement profiles for both 1 shaft and 7 shaft are shown in Figure 4. Figure 4 clearly illustrates an improved alignment between the two pressure profiles. The pressure alignment also implies an improved alignment between the operational schedules at the two shafts. The schedule represented by the pressure requirement still demonstrates a difference. However, the pressure requirement minimum ranges align. The minimum ranges are also found during Eskom peak TOU tariff times, as illustrated in Figure 4.

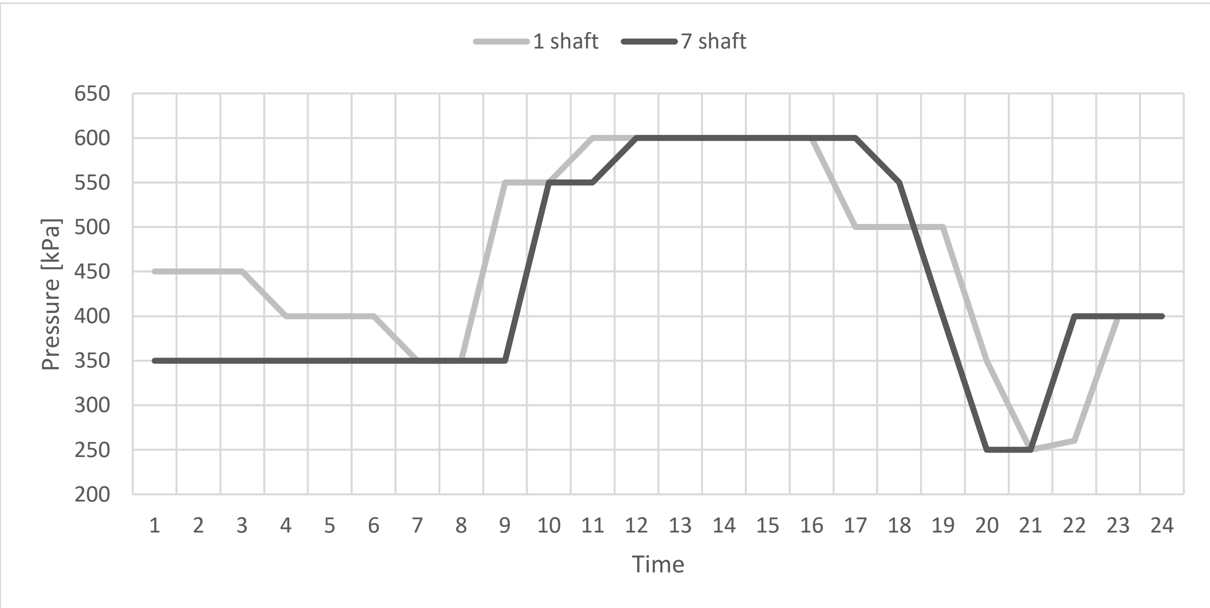


Figure 4: Mine sub-system pressure required for maximum savings scenario

Figure 5 illustrates the schedule adjustment for the power consumption change regarding the maximum savings scenario. The effect of the schedule changes is shown in Figure 5 by the arrows. Figure 5 illustrates, as previously described that the power consumption reaches a minimum during peak TOU tariff times (07:00-11:00 and 18:00-21:00). It was after this fact that the first scenario became representative of the maximum financial reduction.

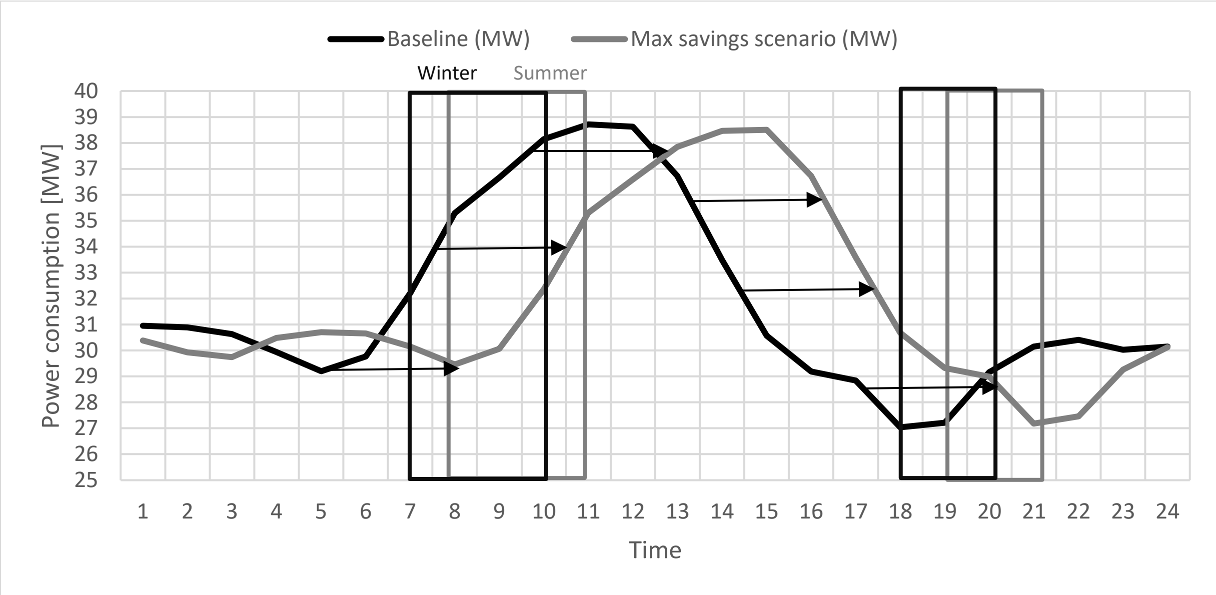


Figure 5: Maximum-savings scenario power consumption comparison

The effects of the proposed schedule are indicated in Table 2.

Table 2: Max savings scenario's schedule adjustment effects

Shaft	Shift	Old start	New start	New end	Difference (h)
1 shaft	Drilling shift	06:00	09:00	19:00	3
1 shaft	Afternoon shift	19:00	22:00	05:00	3
7 shaft	Drilling shift	05:00	10:00	18:00	5
7 shaft	Afternoon shift	16:00	21:00	01:00	5

Realistic schedule adjustment

The proposed schedule was deemed too extensive and would have been difficult to implement in a mining system with a minimum of 8000 workers present during the average working day. The proposed adjustment of three hours at 1 shaft would likely not be feasible. The shaft has at least 1.5 times more working personnel than 7 shaft. After this fact, it was decided to analyse a realistic scenario. The realistic scenario was not necessarily a representation of the best financial reduction. However, it had a much larger probability of being implemented. Figure 6A illustrates the pressure requirements of each shaft. The alignment between the two pressure-requirement profiles of the two shafts was isolated and illustrated by the black blocks.

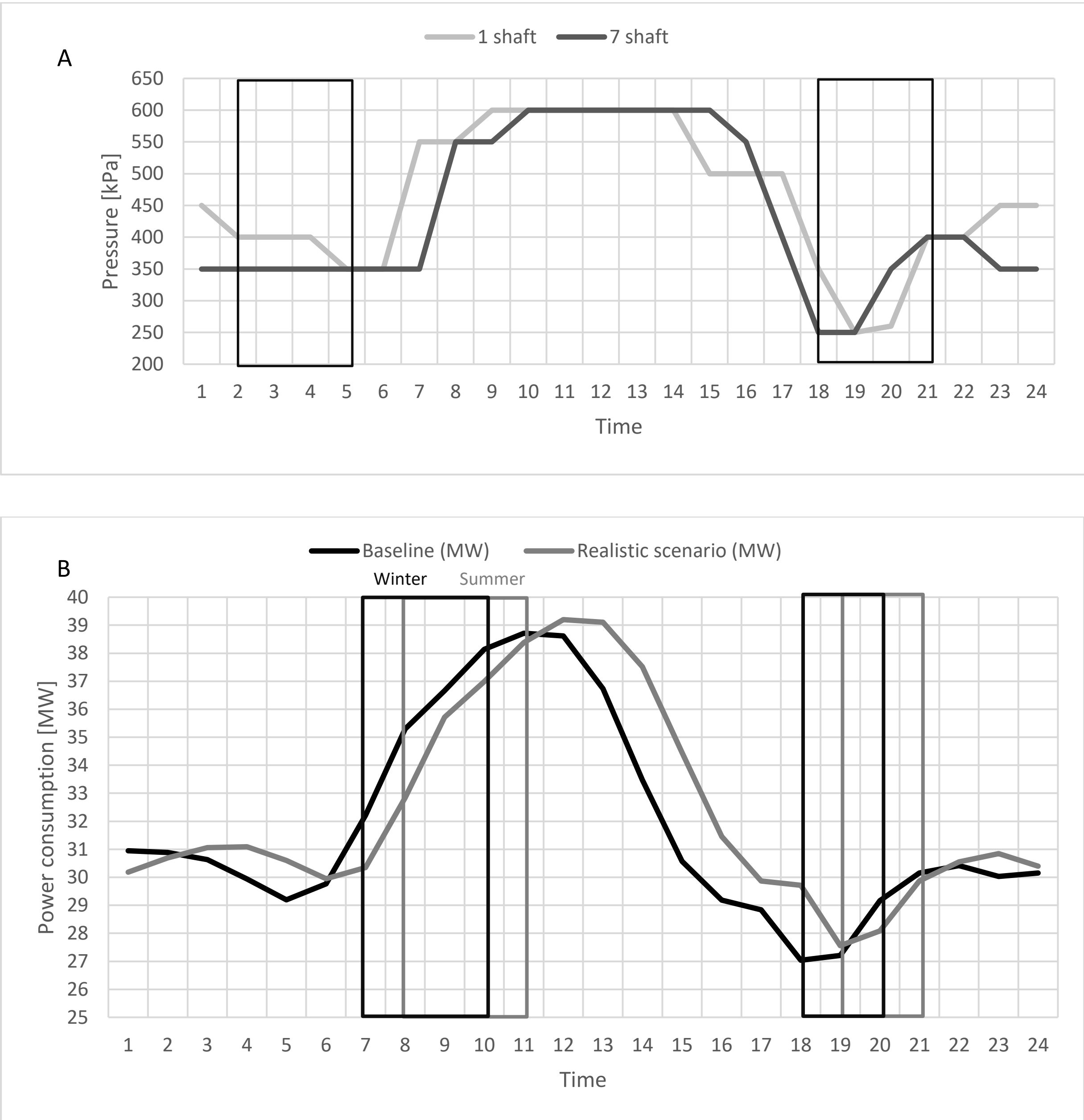


Figure 6: (A) Realistic scenario pressure requirements, and (B) resulting power consumption change

An irregular occurrence can, however, be seen during the morning. 7 shaft drilling shift starts at 07:00 and 1 shaft drilling shift begins at 05:00. 1 shaft is, however, the larger of the two shafts. The only component dependent on both these shafts' schedules are the compressors. In this case, however, the compressors were adjusted to supply to 1 shaft as this shaft was also the primary user of compressed air. The power consumption profile in Figure 6B illustrates only a slight change between the baseline graph and the realistic scenario. The power consumption represents the forward adjustment of 7 shaft by three hours and 1 shaft by one hour.

The schedule of 7 shaft closely represents the schedule of 1 shaft. The relatability between the shafts was also apparent from the resulting new pressure requirements illustrated in Figure 6A. Table 3 indicates the schedule adjustment effects.

Table 3: Realistic scenario schedule adjustment effects

Shaft	Shift	Old start	New start	New end	Difference (h)
1 shaft	Drilling shift	06:00	07:00	17:00	1
1 shaft	Afternoon shift	19:00	20:00	03:00	1
7 shaft	Drilling shift	05:00	08:00	16:00	3
7 shaft	Afternoon shift	16:00	17:00	23:00	3

Figure 6A shows that during the morning no substantial adjustment was made regarding morning peak TOU tariff times, whereas the evening power consumption has adjusted to a slight degree and still decreases during the evening peak TOU tariff times. However, no substantial changes have been made with regards to the peak TOU zones and in comparison with the baseline power consumption.

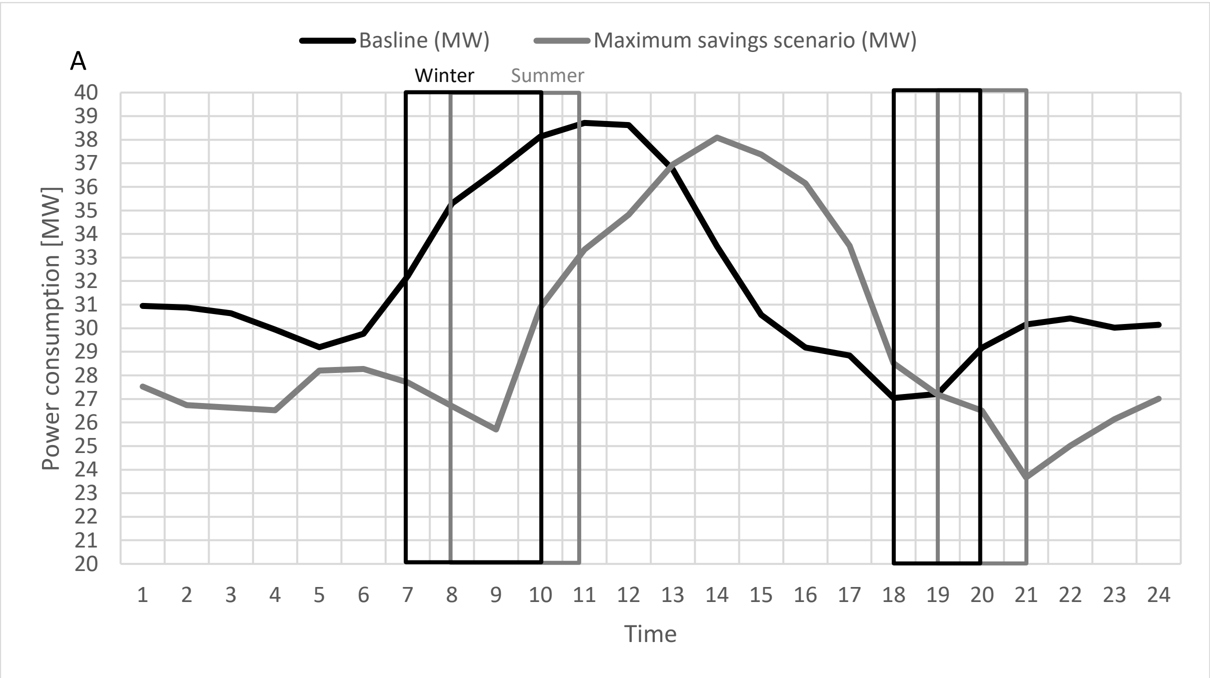
The proposed adjusted schedule at 7 shaft relates closely to the schedule of 1 shaft, which illustrates the implementation of the proposed adjustment schedule is possible.

Possible improvement simulation

The purpose of the schedule adjustment was ultimately to align the power demand. An alignment of the power demand led to a potential reduction in power consumption during low-demand times. This reduction of the power consumption of a component was simulated using past reductions implemented in numerous studies. The total power consumption was then again calculated using the reduced power consumptions.

Figure 7A describes the maximum savings scenario in combination with the energy reduction possible, as per the newly proposed schedules. Figure 7A illustrates a reduction mainly during peak TOU tariff times in the morning and part also, during the evening.

The same reductions were implemented in the realistic scenario. The nature of the schedule alignment was consistent with the requirements for the simulation of potential reductions. Figure 7B illustrates an apparent reduction in power consumption during the morning and evening peak TOU tariff times. The power consumption also reduces on average.



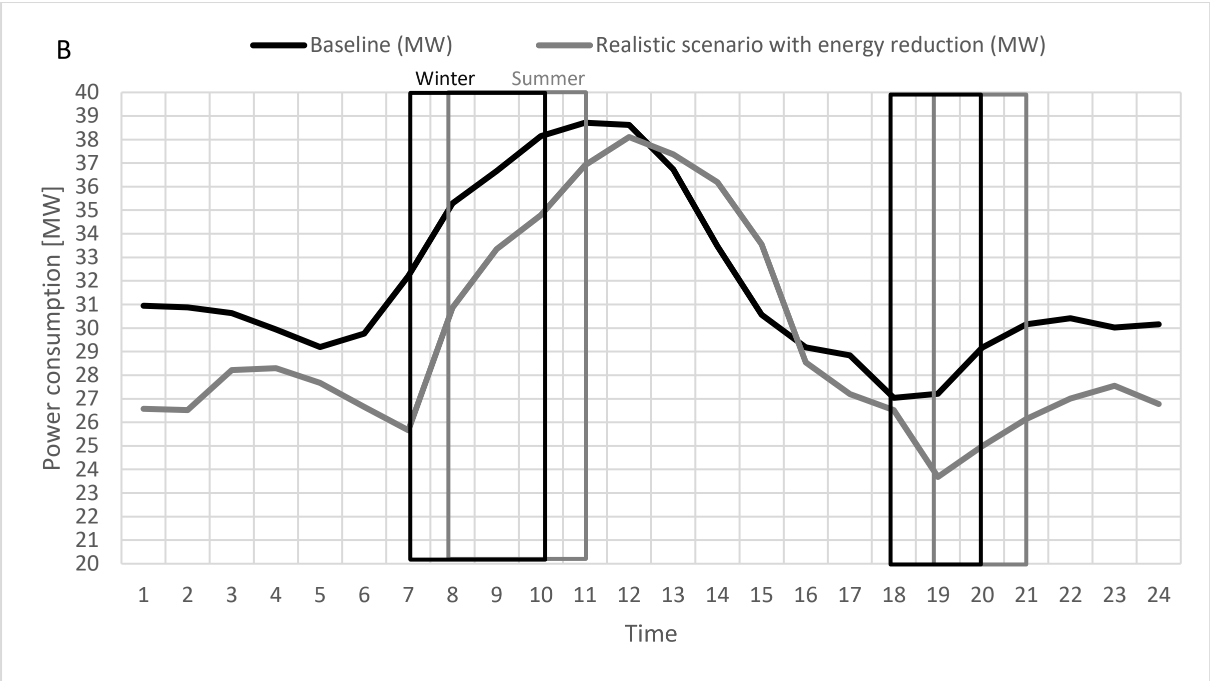


Figure 7: (A) Maximum savings scenario and possible improvements, and (B) realistic scenario with possible improvements

Financial effect

Table 4 shows the financial implication of the proposed schedule adjustments. The initial financial impact of only applying the proposed schedule adjustments was noted. The total system power consumption cost regarding these two sub-systems was estimated. It was determined to be approximately ZAR160 million per annum, with specific regards to weekdays. The maximum savings scenario heeded a ZAR2.1 million financial cost reduction. The realistic scenario led to a ZAR1.1 million cost reduction.

The primary purpose of this study was to analyse a mining system in its entirety with regards to integrated load management. The evaluation concludes with a financial analysis to illustrate the effect of different proposed integrated load management simulations. The possible power consumption reductions were estimated and led to a ZAR12.2 million financial cost reduction when applying the realistic scenario. An ZAR13.5 million cost reduction was determined for the maximum savings scenario.

Table 4: Financial implication of proposed adjustments

	Financial reduction max savings (%/annum of total)	**Financial reduction realistic (%/annum of total)**
Schedule change	1.3	0.7
Potential improvement	8.4	7.6

Discussion

From the study, it becomes quite clear that the potential exists for cost reductions on the mine based purely on the TOU tariffs. Current operations at the mine cause some systems to peak or increase during peak TOU tariff times. This increase in power consumption during peak TOU times could mainly be attributed to the compressors studied at the mine. High demand times were found during both peak TOU tariff time ranges.

Regarding the TOU tariffs, it was found that by moving only the shifts of the different shafts to a more appropriate time resulted in positive repercussions. The aim was, however, to align the schedules to the times on the mine as well, where the demand was the least possible. The low power consumption times also correlate with the air demand. The compressors were also found to be the most important and largest consumers. The compressor power consumption was related to the air pressure requirement. The air pressure requirement was in turn connected to the mining operational schedule.

When aligning schedules from different subsystems, the effect of the peak TOU tariffs was maximised. The maximum cost reduction was found where the two shafts' blasting shifts were aligned. The blasting shift describes a time when little happens on a mine as it is dangerous for personnel to be underground. This fact meant that all the systems experiencing a power consumption minimum during this time would be affected by the schedule change. The same can be said about the end of an evening shift when personnel are exiting the mine. A gap forms between evening shift and the next drilling shift. Initially, the schedules of the two shafts on the ring varied considerably. 7 shaft underwent blasting shift from 13:00 to 15:00. This while 1 shaft experienced blasting shift from 17:00 to 19:00. The schedule inconsistency indicates a four-hour difference.

The realistic scenario illustrated a proposed schedule change which was more realistic and possible to implement. The consumption reductions that were estimated were not definitive. These reductions are dependent on the implementation of multiple energy efficiency projects. Throughout the study, the compressors were found to be the most significant power consumers. The compressors were found to consume 55% of the total power consumption of the mining system. Compressor demand during non-drilling shift times is mainly dependent on the efficiency with which air is used. During blasting shift, the air demand is dependent on the ability with which air consumption can be reduced regarding the shafts. The compressor control can only be adjusted or improved further based on the shafts' demand.

The study can be used to illustrate the potential implications of integrated load management and operational schedule optimisation on the power consumption and cost savings in the mining industry. Chatterjee *et al.* illustrated the effect of mine schedules on ventilation demand in their study [7]. The ventilation fan usage was looked at in an integrated fashion. Badenhorst *et al.* illustrated the effect of downtime and changed schedules in rock hoist optimisation in their study [31]. Integration with demand side management was also in the scope of the study [31]. Peach *et al.* and Booysen *et al.* illustrated, consecutively, the improvement of control philosophies in refrigeration [42] and compressed air systems [37] in their studies. We took it further by holistically analysing a mine regarding its power consumption and operation schedule. An integrated load management solution was illustrated, which includes all the power consuming components on a typical platinum mine.

Conclusion

The primary purpose of this study was to analyse an entire mining system with regards to integrated load management. The analysis was used to illustrate the possibility and implication of integrated load management. The degree of reduction caused by the simulated improvements was dependent on a statistical analysis described. It was also dependent on the actual energy improvements on similar systems, as found from the existing literature. Individual power consuming components were isolated. The components were analysed regarding their dependency on the operational schedule, other mining systems and other power consumers. The analysis was found useful when applied to a mine and in getting information regarding a specific system. The analysis results were also found beneficial regarding the realistic reduction potential of power consumers based on literature.

Future work may include but is not limited to, the practical application of the changes described and actual cost reductions that were found during the implementation. It may also include a detailed questionnaire and a method used to present the idea clearly and concisely to the right personnel at the mine.

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2 App. A.2: Journal of Energy in Southern Africa guide for authors

Peer review process

This journal uses a **double-blind review process**, which means that both the **reviewer** and author identities are concealed from the reviewers, and vice versa, throughout the **review process**.

The Journal of Energy in Southern Africa continues to expand its reviewer database to facilitate a quicker turnaround of publications. Firstly, to satisfy the double-blind review condition, authors should exclude their names and affiliations in the original manuscript at the time of submitting. A notification will be sent to the corresponding author to add these details at an appropriate time, usually at the end of a satisfactory review process. Secondly, if the reviewers chose to use track changes, they are requested to change their PCs user names to Reviewer A, B or C while working on the MS document under review: Go to File/options/username and change accordingly. Otherwise reviewers can create a new file and comment according to the line numbering in the original submission.

It is mandatory for the authors to give four proposed reviewers and their credentials when submitting an article (credentials include: title, name and surname, including middle initial when available, organisation or institution, discipline or faculty or department, position or role, email address). These proposed reviewers must be added under 'Comments for the Editor' during Step 1 of submission process. Potential reviewers can most likely be those that have published in at least one 1 accredited international journal in the last five 5 years and (optional) may be sourced from the list of your references. Such reviewers most certainly have expect knowledge of the topic at hand. Any possible conflict of interest with the proposed reviewer must be disclosed to the editor. Such a conflict of interest would include the following.

Such a conflict of interest would include the following - when the proposed reviewer:

- has co-authored with current authors before,
- was affiliated with the same organisation/institution as the authors' during the last 3 years,
- has played a role in funding mechanisms for the research,
- has personal/special relationships with the resources of research (e.g. equipment suppliers, employees of affected organisation and owners of technology), or
- is associated with the competitors or the opposition.

It is the editor who assigns author's submissions to reviewers and the editor retains the right to use or not use the proposed reviewers.

APPENDIX B. USING SPECIFIC ENERGY AS A METRIC TO CHARACTERISE COMPRESSOR SYSTEM PERFORMANCE

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Using specific energy as a metric to characterise compressor system performance

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1 App. B.1: Article II

Using specific energy as a metric to characterise compressor system performance

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Abstract

Mine compressed air systems are inefficient and complex to analyse. There is no clear method which can be used to characterise the total performance of the supply side system in terms of the air supplied and energy consumed. A simplified and unbiased performance measuring method was lacking from research. An important implication of this study was to develop a simplified method which uses a single metric to determine the performance of a compressed air system relative to the compressor air supply and energy consumption. This metric used minimal information and can be used as a guide to improve performance as well. A compressed air system was analysed before and after project implementation, using the simplified method. The simplified method gave a good indication of the performance change as projects were implemented on the compressed air system, with an improvement of 6 % on the average total specific energy from 104 to 98 Wh/m^3. The off-peak specific energy decreased from 103 to 94 Wh/m^3 which illustrates a 9 % improvement. This study showed the possibility to characterise the performance of complex compressed air systems using a simplified metric. It can also be utilised to verify whether supply side initiatives were effective.

Keywords:

Specific energy, compressed air system, compressor, simplified method, energy

Introduction

CASs vary in size and are extremely complex in terms of their setup. This is illustrated in studies done by Schutte *et al.* and Mousavi *et al.* where different types of compressors (centrifugal [1] and rotary compressors [2]) in different configurations were required to meet differing compressed air demands [1, 2]. CASs were typically found to be energy intensive [3] and inefficient [4].

CASs consist of two major components, mainly the compressed air supply (compressors) and the compressed air demand (end users using compressed air) [5]. These components are connected through a compressed air network consisting of pipes [5]. There are various inefficiencies in such networks and studies have found that typically only 10-30 % of compressed air (CA) reaches end users [2].

Inefficiencies and performance decreasing factors are usually found to be present on both the demand side of a system as well as the supply side [1, 3]. The supply side typically consists of multiple compressors while factors affecting the supply side includes but is not limited to control strategies, compressor configuration and compressor pressure set point controls [1, 5]. The demand side inefficiencies usually consist of poor usage and poor compressed air maintenance at the compressed air users, with leaks usually being a large focus point [1, 5].

Furthermore, there are substantial differences in pressure demand between end users, requiring both high and low pressure on same compressed air networks [1]. It is therefore difficult to analyse such a system completely without in-depth knowledge of the system [3]. Mousavi *et al.* highlighted the importance of understanding the system and compressors with regards to system performance and efficiency [2].

Various methods to analyse CASs exist in literature, however each have their own set of advantages and difficulties. Seslija *et al.* describes a systematic approach where the process starts with an audit and system analysis [3]. A difficulty that arises with doing an audit on a complex system is that it will likely be time consuming and have a high financial cost. Jiang *et al.* describes an analytical model which was developed from first principles for the purpose of predicting compressor performance based on geometric information [6]. This method takes into account different parameters which may not always be easily determined in actual systems, as well as characteristics curve studies that may be rather difficult to implement as changes are made on the system [6].

Friden *et al.* used a simulation model built in Simulink from the CAML (Compressed air model library) which utilises an audit of the air usage pattern and user defined requirements [7]. The simulation model generates system configurations with alternative equipment and computes the predicted life cycle cost [7]. It also selects the configuration which meets the specifications and leads to the lowest life cycle cost [7]. The simulation model is however complex and requires an audit to be done, which will likely be time consuming and difficult.

A study done by Paraszczak clearly defined how to understand and assess mining equipment in terms of different factors such as availability, utilisation and production efficiency [8]. Paraszczak used a mathematical model to understand and assess mining equipment effectiveness. Different factors were taken into account in this model such as availability, equipment utilisation and production efficiency [8]. The difficulty of this method pertains to the parameters mentioned not necessarily being measured or known. The method also does not specifically focus on a CAS but can be applied to certain components thereof.

From literature we can conclude that understanding the performance of complex CASs is difficult and time consuming. However, in the study by Mousavi *et al.* the authors made use of the specific energy (SE) metric (simplified metric) as a performance indicator and to grade compressors. They found that the use of this metric led to the knowledge required to utilise more efficient compressors to meet the air demand better [2]. Therefore, it may be possible to use SE as a simplified metric to determine the performance of a complex compressed air system where limited data is available. Giacone and Mancò illustrated the use of SE in their study on energy efficiency in industrial processes [9]. The study found that SE was effective in measuring a system’s performance but that it was also necessary to add other metrics in the specific case. A study done by Benedetti found that energy measuring, controlling, budgeting and forecasting are rarely performed in regards to the CA production [10]. Furthermore, Ganjehkaviri *et al.* found that as the efficiency of compressors increased it caused an increase in exergy efficiency as well as in total cost [11].

The study done by Mousavi *et al.* illustrated the utilisation of SE during the analysis of a compressor combination to decide which compressor combination best suits the demand [2] and a study done by Afkhami *et al.* illustrated the use of different forms of SE to compare energy savings actions in a cement production plant [12]. The study analysed the energy efficiency of compressed air systems and studied different compressor configurations and the use of different settings to predict the energy requirement of the system [2]. The method described was used to firstly determine the compressor priority, after which the effects of changing the maximum capacity of the compressor supplying base load was analysed [2].

Paraszczak [8] identified the need for a simplified method to determine system performance with little time in hand. Current methods typically make use of simulations [13], audits [3] and analytical models [14] to evaluate a CASs performance which are complex and time consuming methods. In the study by Mousavi *et al.* [2] the SE metric was used as a key performance indicator however, it was not used to analyse the CASs' performance throughout operation.

It was found throughout literature that there is a need for a less complex method which can be used to analyse a complex CAS throughout operation and measure the performance of said system. The method must be applicable to any type of mining CAS. The aim of this study is to determine whether a simplified methodology, making use of the SE metric, can be used to characterise and evaluate the performance of a complex CAS. SE will be tested as a simplified metric to measure the performance of the supply side of a CAS throughout operation. The appropriateness of SE as a metric to analyse CAS performance will be achieved by evaluating specific energy CAS performance before and after optimisation projects were implemented.

Methodology

Overview

A generic method is defined in this section with the purpose of testing the appropriateness of SE as a metric for CAS performance. The purpose of the methodology was to test whether this simplified metric could be used to characterise the performance of a complex CAS. In brief, the SE metric was tested by measuring performance on a complex CA network used in the deep mining industry. The metric was determined before and after various efficiency projects were implemented.

Performance metric

CASs most often consist of multiple compressors to ensure redundancy and maintain system availability [1]. Equation 1 defines the specific energy (SE) of a compressor or CAS.

$$SE = \frac{P}{f} \tag{1}$$

In Eq. (1), the SE of a compressor is described by the rated energy consumption (P) of the compressor and the supply flow (f) at said energy consumption. If the SE of a CAS is to be determined, the total energy consumption and total supply flow will be used. Increasing SE indicates decreasing efficiency while decreasing SE indicates increasing efficiency.

Ideal system baseline

A CAS consists of different compressors operating during different times of the day, as illustrated in a host of studies [5, 1]. Therefore, no CAS is exactly the same each day and thus a normalised state of compressor operating times over a monthly period was selected. The compressors, which were used 90% of the time, were considered the baseline compressor configuration.

In this section the normalised operation state of the CAS was combined with ideal SE of each compressor that operates during a normal day in the life of the system. The next step was to combine each compressor's SE and normal operating times into an ideal SE of the total system, to which the system's SE as whole can be compared. During each time interval, an average was taken of the SE of the compressors operating during that timeslot which takes a more in depth view than in the study done by Mousavi *et al.* [2]. This was then used to graph the ideal SE curve.

Actual system operation and data analysis

Data for the actual system operation was obtained from the data logged by the mine supervisory control and data acquisition (SCADA) system. The SCADA system had data relating to the average energy consumption in 30 minute intervals and compressed air flow in 10 minute intervals. The SCADA system receives energy consumption data from power meters and compressed air flow data from flow transmitters. The running status, running duration and date for each compressor in a CAS were also available from the SCADA system. Unfortunately, data quality at the mine in question was not ideal and some data quality checks were required.

Fig. 1 illustrates a typical dataset received from a mine for a compressor. As seen from the graph, there are irregularities in the data which will not drive useful knowledge of the system when included into the processed data. It was found that filtering the data to only include relevant data into the final data analysis was necessary. When a pattern of irregular data is seen however, it must either be included in the analysis or investigated to understand its causes and effect. The purpose of this step is to achieve an understanding of the normal operation of a compressor and thus of the system.

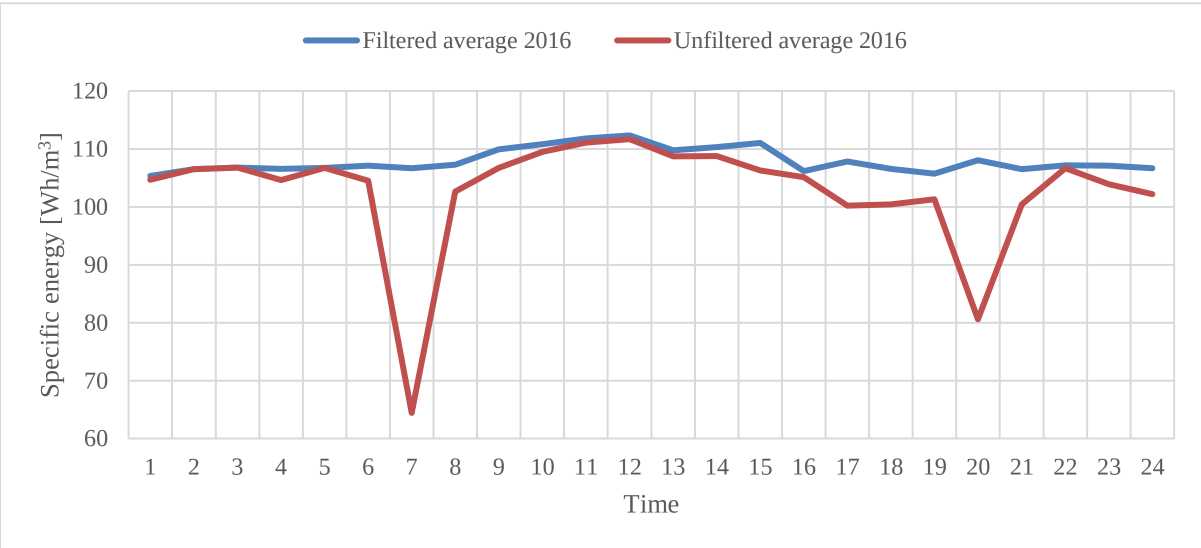

Figure 1: 2#_VK40_2 filtered and unfiltered average specific energy

The filtering process was firstly done to minimise the effect of data loss and data irregularities. Secondly, the filtering process was done specifically to filter out the effects of compressor start-up and shutdown irregularities which can either consistently lead to a much higher or lower SE than that found during normal weekday operation.

Data loss or irregularities can be described as:

- Data fluctuating from normal operation to 0 between one time interval and the next,
- data flatlining at a specific value,
- data limiting out and flatlining and
- energy consumption going out of range of the rated and possible minimum power demand of the compressor leading to irregular (extremely high or low when looking at the normal operation of said compressor) SE value.

Data irregularities caused by compressor operation includes:

- Blow off being initiated during start-up and shutdown leading to supply flow being much lower than power consumption and
- SE value that is out of the normal operation range, either to high or two low compared to, firstly, the rated specifications and secondly the normal compressor operation.

Data filtering allowed for normal system operation to be analysed in terms of its performance. Compressor start-up and shutdown leads to spikes in specific energy which are not representative of the performance changes over the long run. Compressor start-up and shutdown usually involves the most air to blow off leading to a largely reduced supply whereas the energy consumption has already increased significantly. The filtering is necessary as to analyse the system performance and specifically focusing on a compressor's operation on a specific day is beyond the scope of this study.

The compressors' SE was then compared to the ideal SE of each compressor and in the case where historical data is available, it can be used in the comparison where the average during peak and low demand times were compared. The statistical standard deviation was also calculated where a large STD meant there was a large difference between the SE at different time intervals and a small standard deviation illustrated small deviation in compressor SE. This can already lead to improved knowledge of the system as it will give an indication of an inefficient compressor or system.

If individual compressor SE cannot be calculated, the total system SE can be calculated and used for comparison using the total compressor system energy consumption and the total air supplied.

System data analysis

The performance of the compressors was scrutinised once the baseline SE and actual SE for a period were calculated. Individual compressor performance was prioritised by either high priority (red), medium priority (yellow) or low priority (green). The priority was based on three conditions. The first condition was the type of duty in terms of a baseload compressor (compressor was always operated) or a trimming compressor (operated as required by system pressure and flow demand). Table 1 illustrates the scoring philosophy used.

Table 1: Compressor performance analysis scoring philosophy

Score	0	1	2
Duty type	Trimming		Baseload
Size of compressor	Smallest compressor (<30% of largest compressor)	>=30% and <=60% of largest compressor	Largest compressor on network
SE difference from baseline	0-6.25%	7-12.5%	>12.5%

In Table 1:

a compressor with a score larger and equal to 4 was a high priority compressor and is coloured red in the Results and discussion section. A compressor with a score equal to 3 was of medium priority and coloured yellow in the Results and discussion section. A compressor with a score lower than and equal or equal to 2 was a low priority compressor and was coloured green in the Results and discussion section.

The SE difference percentage was determined from a study by Vermeulen *et al*. which investigated 25 case study mines and discussed an average difference in the compressor energy consumption at all the mines[15, 16]. The benchmark was set at 25% in this study before any improvement projects were implemented [15, 16]. As SE differences are much less pronounced 25% of said 25% was taken for the first tier and between 25% and 50% for the second tier. Above 50% was used for the third tier.

This was a crucial step where scope for improvement of the system was to be established. Investigation into possible projects was started after this step, where areas where the system could easily be improved were established. This in turn guided the investigation of the compressor system in a specific direction or likely to a specific compressor. Understanding of the simplified metric led to a better understanding of the system.

Validation

The final step in the methodology was verification of the project/projects that were implemented. The performance of the system was compared to the ideal performance as well as the historic performance determined through the SE. The statistical analysis was repeated using the new data of the improved system and also compared to the historic system data.

This step was critical to verify any project and establish if a notable improvement could be seen in the system operation which was usually not done intrinsically [5, 1]. It was thus repeated for the sake of better understanding that the SE metric combines the energy consumption of the system and the air supplied. An improvement in the system directly correlated to a lower SE, which in turn described a lower consumption of energy in relation to the air delivered. This may have been caused by, but was not limited to, any number of projects implemented on a system.

The success of the simplified method was dependent on whether either an improvement or a decrease in system performance was seen after a projects implementation. The new method's success is also dependent on whether it could be used to plot performance and use this improved knowledge to make better decisions. It was also based on whether the performance of the system and/or an individual compressor could be analysed using the simplified method. If a project was implemented with the purpose of increasing compressor performance this would need to be seen on a SE graph for the method to be feasible. The method must also make it possible to efficiently characterise compressors.

Results and discussion

Overview

The case study presented in this section is a platinum mine in South Africa. The complex CAS comprised of one compressor with approximately 10 kilometres of piping on surface. The compressed air was generated by nine compressors of different rated sizes. The compressor size ranges from 1 MW to 8 MW in this section. The air supply ranges from 10000 m^3/h to approximately 95000 m^3/h. The total energy consumption reaches a maximum of 24 MWh. The compressor operation and running compressors will be illustrated in detail. Fig. 1 illustrates the compressor positions relative to the system as well as to each other, whilst Fig.2 illustrates the supply curve of the compressors.

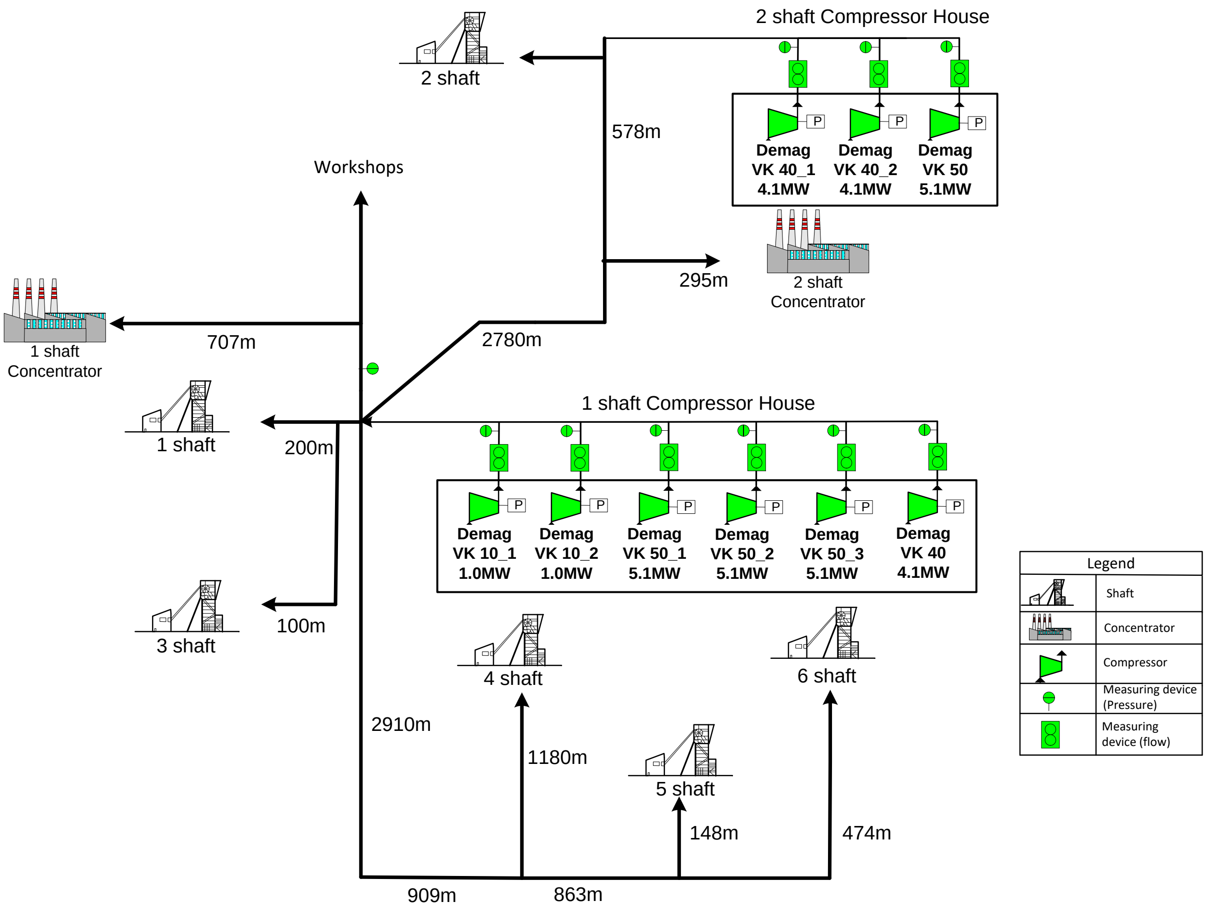

Figure 2: Platinum mine compressor and demand layout

A Platinum mine was used as case study system as Platinum mines usually consist of various demands (in this case shafts) [17], especially when compared to Gold mines. Gold mines usually also consist of various compressor but the norm is for the compressors to be dedicated to one shaft, either on a system only consisting of one shaft [18] or on a system with numerous shafts [19]. A Platinum mine compressed air system usually consists of larger, more complex compressed air configurations.

The CA demand of this system follows the typical trend in mining with increased airflow required during the drilling shift between 5am and 2pm. This is illustrated in the red block highlighted in Fig. 3. A smaller peak is witnessed during the late afternoon/early evening (orange block) which is found during sweeping shift. The supply decreases in the afternoon (green block) when blasting occurs in the mine and during the sweeping shift until the next drilling shift, which is known as the night shift (blue blocks) when no production occurs.

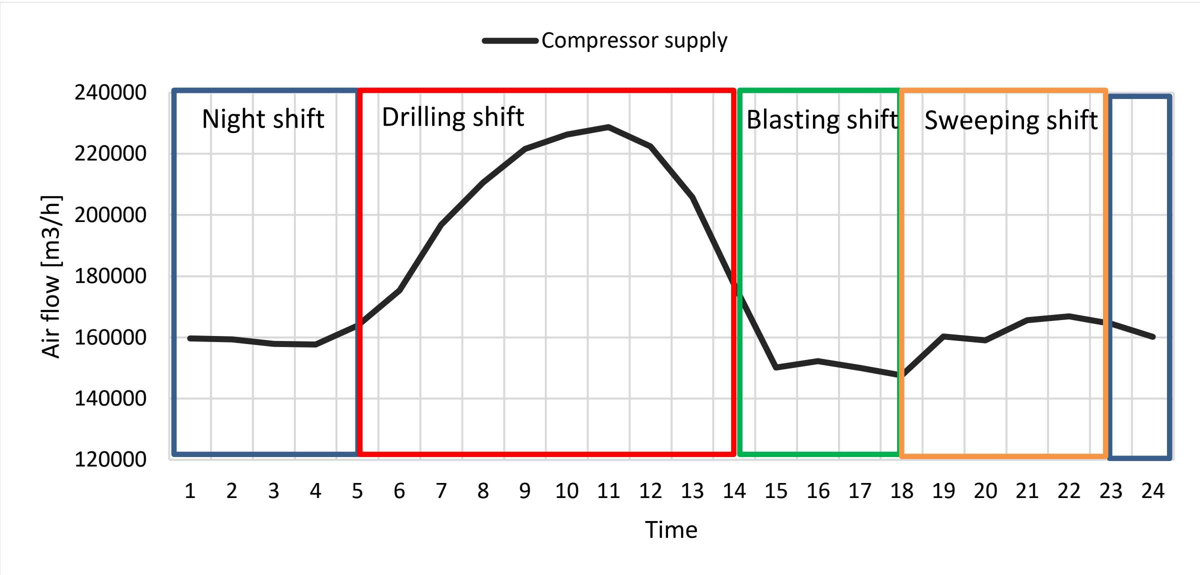

Figure 3: Compressor supply curve

A host of supply side efficiency projects were implemented on the compressed air ring under discussion. The first project focussed on the improvement of the operation and control of compressors through awareness and constant monitoring. This was combined with a compressor discharge pressure set point reduction project, which also contributed to improved supply conditions. Another project implemented was an instrument air improvement project which consisted of improving the air system utilised to start-up and control each compressor. The instrument air system consists of components which include a smaller standalone compressor as well as a pressure vessel. A compressor of this size needs a separate air system to supply compressed air to critical parts of the compressor when it is not yet able to supply compressed air. Table 4 indicates which compressors were affected by which projects.

Table 2: Compressed air project implementation

#	Compressor		Compressed air projects		
		Lowering of pressure set-point	Improved control	Improved scheduling	Improved instrument air
1	1#_VK50_1	X	X		X
2	1#_VK50_2	X	X		X
3	1#_VK50_3	X	X		X
4	1#_VK40	X	X	X	
5	1#_VK10_1	X	X	X	
6	1#_VK10_2	X	X	X	
7	2#_VK40_1	X	X	X	
8	2#_VK40_2	X	X	X	
9	2#_VK50	X	X	X	

The projects were implemented by the mine with the combined purpose of improving CAS efficiency as well as generating financial savings on the mine's electricity bill.

Performance metric

The performance metric was calculated using the applicable equation (Eq. (1)). The purpose was to determine whether the metric can be used to characterise the performance of a complex CAS. The question that we will be persistently trying to answer throughout this section is whether the method, and more specifically the metric, can be utilised to identify scope for improvement on the supply side of a complex CAS. The metric will also then be tested in terms of its usefulness regarding validation of the effect of supply side interventions.

Ideal system baseline

The design specification of each compressor was gathered and used to determine the design SE as indicated in Table 3. Each compressor was also named here in a way that describes it best according to its size and geometric position on the mine. Shaft 1 and Shaft 2 describe two compressor houses which are located on the mine. The compressed air system consists of these two compressor houses and five compressed air demanding shafts/declines.

Table 3: Compressor design specification

Compressor	Rated power [kW]	Rated flow [m^3/h]	Design specific energy [Wh/m^3]	Compressor operation type
1#_VK50_1	5100	56000	91.1	Baseload
1#_VK50_2	5100	56000	91.1	Baseload
1#_VK50_3	5100	56000	91.1	Baseload
1#_VK40	4100	44000	93.2	Trimming
2#_VK40_1	4100	44000	93.2	Trimming
2#_VK40_2	4100	44000	93.2	Trimming
2#_VK50_1	5100	56000	91.1	Trimming
2#_VK10_1	1000	10000	100.0	Trimming
2#_VK10_2	1000	10000	100.0	Trimming

It must be noted that the compressors analysed in the case study have a very high air supply and energy consumption when compared to typical plant or factory compressors [20]. These compressors were used to supply compressed air to a whole compressed air ring consisting of thousands of consumers and multiple shafts. In Table 1 the first three compressors (1#_VK50_1 to 1#_VK50_3) were the baseload compressors. These were almost always operating except when the mine occasionally switched one off over a weekend when the demand was low. The other six compressors were trimming compressors and were only operated during peak drilling times and during other times when the flow demand increased and the pressure was low.

Actual system operation and data analysis

The normalised operation was determined for August 2016 and was combined with the ideal SE to plot the graph illustrated in Fig. 4. This figure illustrates which compressors are operated and during which times they are operated using a Stacked area graph. The figure further describes the systems ideal SE when all the compressors are operating according to their design specifications. The ideal SE can however also be updated continuously according to the compressors operated at the time, as it is dependent on these compressors.

From Fig. 4 it can be seen that between 07:00 and 14:00 the SE on this mine increases during the drilling shift. A slight increase in SE was thus expected as the trimming compressors were switched on. Furthermore, the ideal specific energy (y-axis-right) illustrated by the red line, changed as the compressor configuration changed. Each compressor’s running status (y-axis-left) was either 1 or 0, which indicates either operational or not operational respectively.

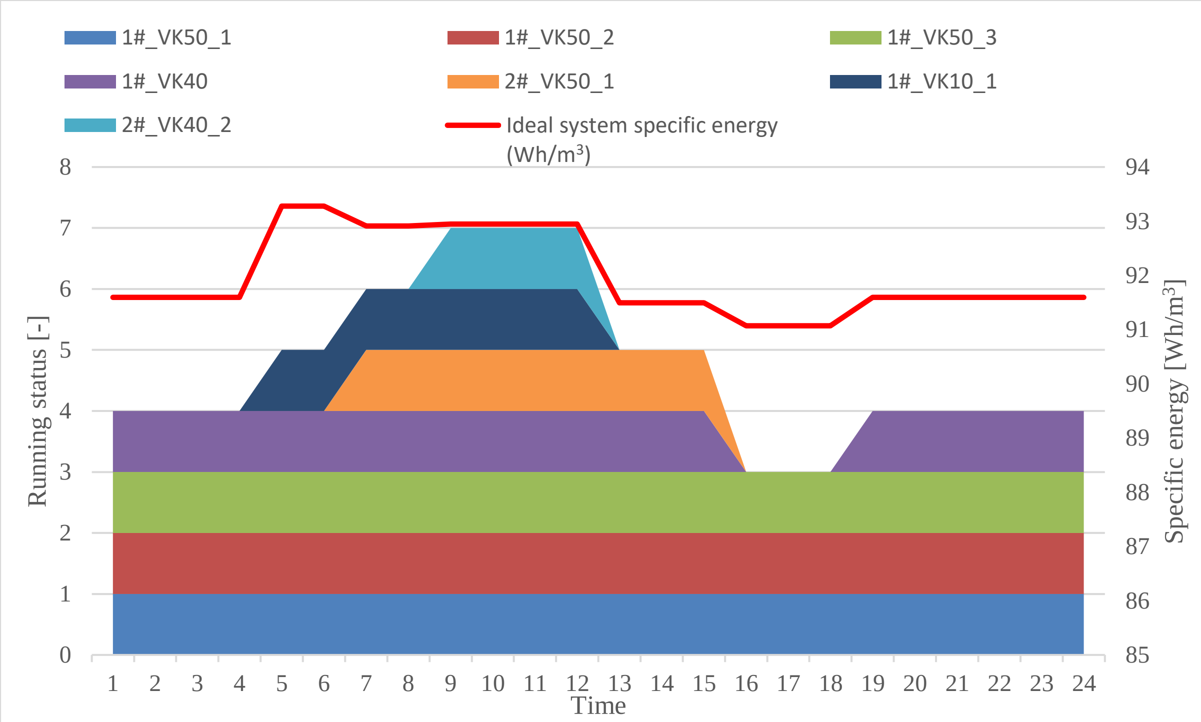

Figure 4: Ideal system specific energy and compressor schedule

System data analysis

The actual systems performance was analysed using historic data from the 2016 year. Table 3 indicates the ideal compressor SE for each individual compressor. The compressors' average SE was determined during peak drilling time, morning shift, afternoon and evening shift. Furthermore, the system analysis described in section 2.5 was used to determine the performance priority/status of the compressors.

Table 4 indicates a substantial difference between the average SE and the ideal SE throughout. Table 4 also indicates only a small difference (1-5 Wh/m^3) between the peak, morning and evening average SE. It now becomes possible to analyse the system for areas/compressors which can be improved. The analysis was based on the simplified metric of SE as it is the basis of this study. A basic understanding of the simplified metric and the rules thereof gave a clear understanding of the system as a whole.

Table 4 indicates the performance analysis done where a compressor was marked according to the colours prescribed in the method (green, orange and red). In this case there were no compressor which were low priority (green) as all compressors had subpar performance regarding SE. Thus, all compressors were either medium or high priority.

Table 4: Compressor performance analysis

Compressor	Ideal specific energy [Wh/m³]	Peak drilling average [Wh/m³]	Average morning [Wh/m³]	Average afternoon and evening [Wh/m³]	Max [Wh/m³]	Min [Wh/m³]	Average [Wh/m³]	Standard deviation [Wh/m³]
1#_VK50_1	91.1	104.9	100.8	100.8	121.5	90.0	101.8	3.7
1#_VK50_2	91.1	97.7	94.2	94.2	107.6	80.8	95.1	2.4
1#_VK50_3	91.1	100.1	97.0	96.9	105.0	85.0	98.0	3.0
1#_VK40	93.2	106.1	103.4	103.2	120.0	90.0	104.5	4.1
1#_VK10_1	100.0	139.2	134.4	134.1	150.0	125.0	135.9	3.0
1#_VK10_2	100.0	126.0	122.0	121.9	138.6	110.1	122.5	2.7
2#_VK40_1	93.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2#_VK40_2	93.2	110.3	106.5	106.9	124.0	95.5	109.5	4.0
2#_VK50	91.1	106.1	101.9	101.5	119.9	90.1	105.7	4.2

As indicated in Table 4, at the time that the compressed air system was analysed the compressors had scope for improvement based on the simplified metric. It can be seen that all the compressors deviate from the ideal SE. The baseload compressors (The 1#_VK50_1 to 1#_VK50_3 and 1#_VK40) each differs from their ideal specific energy and illustrates less than 4 % difference between drilling and drilling shifts based on SE. The 2#_VK50 illustrates a 13 % difference between ideal and average actual SE and the 2#_VK40_2 illustrates a 16% difference which also leads to the conclusion that these compressors are of higher priority and shows scope for improvement. The 1#_VK10_1 and 2 are the smallest compressors in the system and were used as trimming compressors which led to their priority being the lowest.

The compressed air ring showed large scope for improvement based on an analysis of the SE metric. The performance of the system was not on par. An understanding of the simplified metric leads to a better understanding of the system. The following was noted:

- Higher SE illustrates lower performance and vice versa
- A small difference between high demand times and low demand times illustrates a less efficient system as SE tends to increase as more compressors are switched on
- Baseload compressors will likely have a high standard deviation/difference between high and low demand times

Projects already implemented on the system before the simplified method was implemented can be critically analysed to establish whether the system was improved.

Validation

The results from the study on the CAS before implementation of any efficiency initiatives identified significant scope for performance improvements. During the first half of 2017 the various efficiency initiatives described in Table 1 were implemented on the CAS. The performance period was thus selected as the month of August 2017. The simplified SE metric was used. Table 5 and Figure 5 indicate the effects of these changes on the CAS.

Table 5: Compressor statistical analysis after implementation

#	Compressor	Ideal specific energy [Wh/m^3]	Average specific energy 2016 [Wh/m^3]	Standard deviation 2016 [Wh/m^3]	Average specific energy August 2017 [Wh/m^3]	Standard deviation August 2017 [Wh/m^3]	Improvement [%]
1	1#_VK50_1	91.1	101.8	3.7	95.6	4.2	6.1
2	1#_VK50_2	91.1	95.1	2.4	93.6	3.0	1.6
3	1#_VK50_3	91.1	98.0	3.0	96.6	4.2	1.4
4	1#_VK40	93.2	104.5	4.1	105.1	3.2	0.6
5	1#_VK10_1	100	135.9	3.0	135.9	4.1	0
6	1#_VK10_2	100	122.5	2.7	N/A	N/A	13.3
7	2#_VK40_1	93.2	N/A	N/A	106.2	3.8	
8	2#_VK40_2	93.2	109.5	4.0	107.5	4.6	1.8
9	2#_VK50	91.1	105.7	4.2	103.1	4.8	2.5
	Total system		**104.5**	**3.1**	**98.2**	**5.8**	**6.2**

Table 5 indicates a substantial improvement when looking at the baseload compressors (1#_VK50_1 – 1#_VK50_3 and the 1#_VK40, which was not used as a baseload compressor during 2017). The priority has shifted instead to the 2#_VK40_1 and 2 with the other large compressors (1#_VK50_1 to 3, 1#_VK40 and the 2#_VK50) being deemed medium priority. The baseload compressors underwent substantial improvements with a 4.5 % difference from the ideal SE. The system indicated a 6.2 % improvement. The standard deviation improved from 3.1 Wh/m^3 to approximately 6 Wh/m^3, which illustrates a large improvement in the times outside drilling shift.

Fig. 5A illustrates the total system's SE on average per time interval. It can be seen from Fig. 5A that there is an overall decrease in SE during the times that the pressure reduction project was implemented (14:00 – 05:00). In combination with this, the compressor operation was also improved during these time slots with less compressors needing to be operated and the more efficient compressors being started instead. Fig. 5A illustrates that the system operates beneath the best case

SE during the morning. There is however substantial scope for improvement during peak drilling shift as well as some scope during the afternoon and evening.

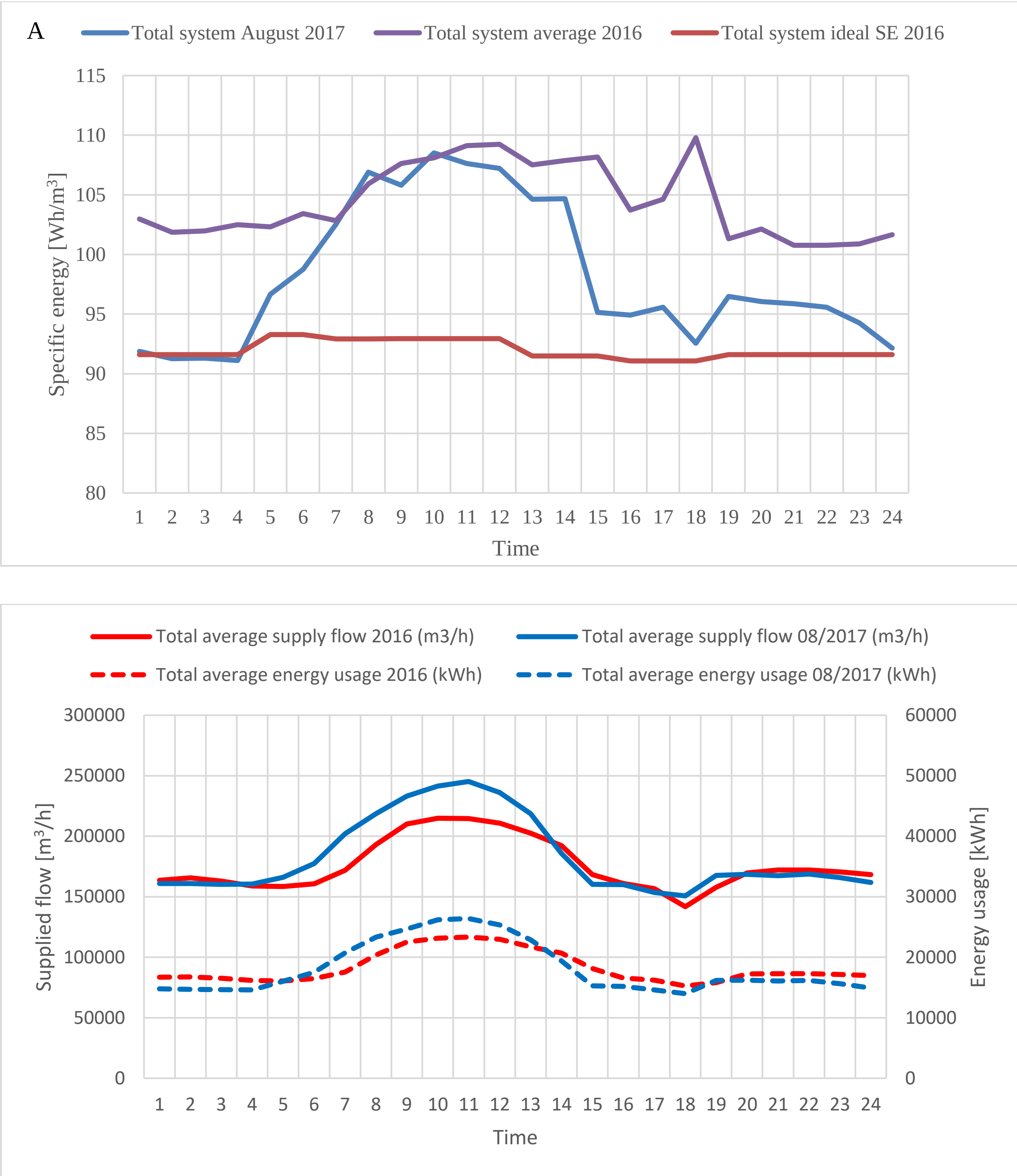

Figure 5: (A) Total system specific energy comparison (B) Total system energy consumption and supply flow comparison

Fig. 5A also illustrates that the large increase during 2016 during blasting shift has now been turned into a sudden dip in SE. During blasting shift, compressed air use in the mine is minimal as there should be no personnel in the mine at this time which leads to less demand and thus less air supplied. The SE should be lower accordingly. The compressors were usually controlled with their guide vanes during this time.

Fig. 5B illustrated the change in energy consumption and air supplied as the system was improved. The rated energy consumption and corresponding supply flow (which describes the ideal SE) was also illustrated. It can thus be seen from Fig. 5B that there were commonalities between the supplied flows and the energy consumed. The supply flow did however increase more when compared to the previous supply flow, whereas the energy consumed did not increase by the same factor which in turn leads to a lower specific energy after projects were implemented on the system. Also illustrated by Fig. 5B is that there was a decrease in the energy consumed during off peak times whereas the supplied flow stayed almost the same. This can clearly be related to an increase in performance.

The SE during drilling shift was still as high as during 2016. This was caused by the difficulty in implementing any project efficiently during drilling shift. Production loss is a clear and present danger to the mine as well as to personnel implementing a project. The mine management will not likely give clearance to a project implemented during this time as it may cause production loss. However, as illustrated by Schutte et al. in the past there has been opportunities for projects.to be implemented during this time and is thus not impossible [1].

The low performance is caused by compressors being switched on even though they are supplying more than what is demanded. It is thus an equipment restraint. There is only a limited number of compressors, as illustrated in Fig. 2*Figure* , which can be utilised. It is thus highly unlikely in this case study for the SE energy of the compressor system to reach its optimal value during drilling shift. During off peak times it is however more likely and it should be further pursued.

Fig. 6 illustrates the analysis of a compressor on a different compressed air system under management of the same mine. The simplified method can thus easily be used from the start to analyse this compressor. When looking at the minimum SE on the graph, the compressor was quite efficient with a value of 84 Wh/m^3. There was a slight increase in drilling peak which corresponds with the case study previously analysed and led to an average of 89 Wh/m^3 outside the low demand time. There was however a large increase in SE during the low demand time when blasting commenced with the average reaching 105 Wh/m^3. This highlighted a problem with the operation or utilisation of this compressor.

During this time (from 15:00 to 20:00) the demand of the system decreased substantially. However, because of the size of this compressor (8 MWh energy consumption and approximately 100000 m^3/h supplied flow) it was unable to be efficiently controlled using its guide vanes. The compressor was larger than what was necessary. This caused the blow off of the compressor to be utilised to prevent it from going into surge, as the pressure will increase beyond its operational safety. As soon as the blow off was utilised, compressed air was blown into the atmosphere which caused the supply to the system to decrease but not the energy consumption. The compressor cannot be switched off during this time since it is not deemed good practise by the mine to switch a compressor of this size off and then on again after a few hours.

By applying the simplified method to this compressor, it can undoubtedly be seen that there is scope for improvement which can also lead an improvement of the system and a decrease in energy consumption.

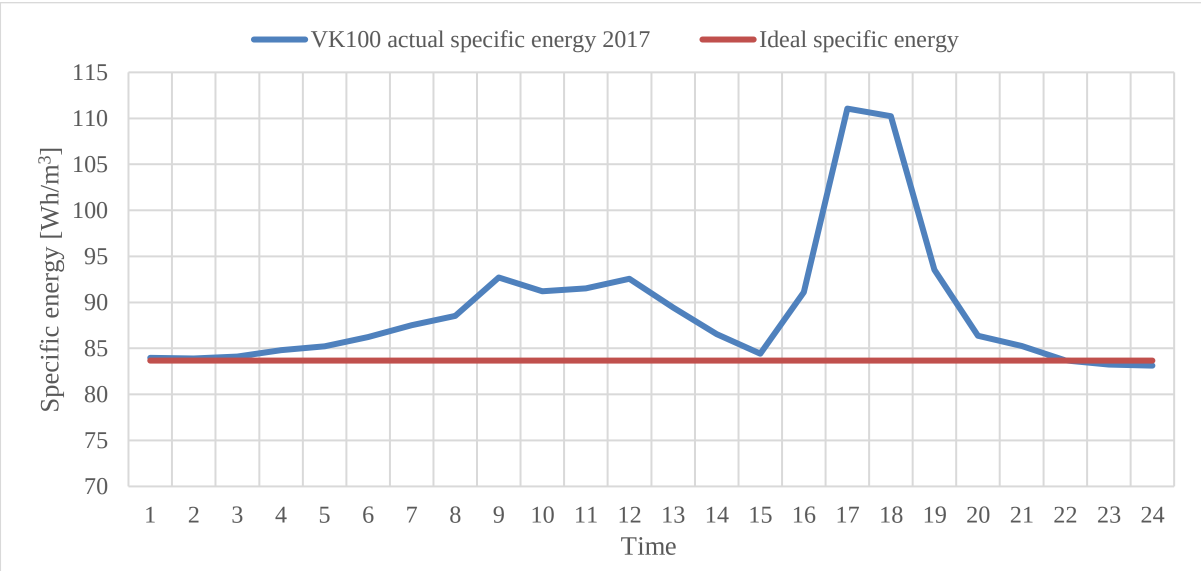

Figure 6: Compressed air system 2 shaft 1 VK100 compressor specific energy

The problem regarding the drilling SE can be solved, at minimum, in two possible ways. The first way can be to include new, smaller compressors in the compressor system. The new compressors will be able to better match the demand increase and will minimise oversupply in the system, which in turn leads to an increase in specific energy.

Another solution may be to improve the control of the compressors. A cost-effective control strategy is illustrated in a study done by Vermeulen *et al.* in which a square butterfly valve was converted to a variable throttle control [21]. Only an actuator and positioner, in combination with a few software changes, were necessary to implement this new control strategy [21]. This control strategy was implemented on a compressor with guide vane control (the same as the compressors in the current study) [21]. The new control strategy takes guide vane control out of the picture [21] which may lead to improved compressor control.

Discussion

The metric used in this study has not previously been used for the specific purpose of investigating and tracking compressor performance [2]. It seems to be to a degree a clear indicator of compressor performance and can track the performance increase or decrease as a project is implemented. The method used in this study was easily applicable on large complex CASs of a Platinum mine due to the limited nature of data required. A basic understanding of the system was however still necessary before the method could be applied.

The method can be used to track the performance of a CAS as shown throughout this study. It will thus be time efficient to apply it to a system as the data used was typically available as it contained important variables in the system. It must be noted that interpretation of the data found was also important to ensure accurate decision making.

The purpose of the study was to develop a simplified method to analyse and monitor performance of compressed air systems in the mining industry. The operation of CASs on the case study platinum mine should be representative of the operation of CAS on most typical gold and platinum mines. In the first case study an entire system was characterised before and after project implementation whereas in case study two, only a specific compressor on an entirely different system was analysed (Fig. 6). These systems were as complex, and likely more so, than typical gold mine compressed air system. The similarity and increase in compressed air system complexity between the two types of mines is illustrated in studies by Marais et al. (platinum mine) [17] and both van Staden et al. [18] and Maré et al. [19] (gold mines). The studies illustrate the similarities between the two type of mining strategies' CAS.

During the review of certain literature studies, the new simplified method discussed during this study could have been used to improve the decisions made throughout. The method discussed can increase knowledge of the system and also complement the methods already used in studies by Jiang *et al.* [6] and Saidur *et al.* [4]. In the study by Jiang *et al.* the method will give additional information when characterising a CAS. In the study by Saidur *et al.* the method discussed may improve the analysis process and add additional knowledge when analysing the effects of improvement projects on CASs. The simplified method could also be used to track compressors' performance using different control modes [13, 22] as well as to measure performance during different compressor schedules [23] and configurations [24].

Saidur *et al.* stated that a variable speed drive on the driving motor of a compressor could potentially save energy and improve compressor efficiency [4]. This could be substantially beneficial as we found that the compressors in our study operated at full load for only a part of the day. The simplified metric (SE) could also have been efficiently utilised to analyse the CAS before and after the initiatives were implemented, simplifying the process of analysis.

A compressor's operating point changes according to the specific control strategy used such as inlet guide vane control, suction throttling, discharge throttling, motor speed adjustment and flow recycling [22]. Control modes for small reciprocating and rotary compressors include start/stop, load/unload, inlet modulation, auto-dual, variable displacement and variable speed control [13]. These methods would have also changed the SE of a compressor as the energy consumption changes and/or the supply changes. For instance, in the study by Jovanovic *et al.* less flow from each compressor was necessary to fill the reservoir [14]. This also meant that compressors were utilised more efficiently to increase the pressure. The SE metric could thus have been used in the above studies to efficiently analyse the performance of the system as well as the methods being applied.

The SE metric could also have been practically applied to analyse the control modes discussed in real time and thus also isolate problems in the system or control mode as the metric takes the supply and energy consumption of said compressor into account. It could be beneficial to additionally use SE to prioritise and control a compressed air system automatically whereas it could better prioritise the necessary compressor during a specific time for a specific air demand.

In a study done by Al-Busaidi and Pilidis, the effects of compressor shutdown and maintenance on the polytropic efficiency of each stage was investigated [25]. It was found that efficiency usually decreased substantially after a maintenance shutdown because of a build-up on the compressor blades [25]. The SE metric could have been used in this case as an efficiency monitoring tool. It could be used in place of any efficiency to get a clear indication, when used in depth, of the performance changes of a compressor.

It was also found from an analysis of the results that a good estimate for an ideal SE value of a compressor on a mine was approximately 90-91 Wh/m^3. This value was however not always applicable and it can only be chosen after analysis of both the air flow supplied and energy consumed of a compressor. In the case where the normal operation of the compressors cannot be seen from analysis or where it was not feasible since the operation changes too much, it may be deemed good practise to calculate and plot the ideal SE for each possible state of the system.

The new method proposed was clearly applied to a complex CAS to determine the current performance status. Analysis of the results shows that the simplified metric was successful in indicating scope for CAS performance improvement as well as monitoring the impact of efficiency initiative implementation. The results in the study were achieved on a platinum mine compressed air system. Further research will be necessary to make conclusions based on other types of CASs such as industrial CASs. The simplicity of the metric however leads to the perception that the method will work efficiently to simplify complex systems.

Conclusion

The objective of our study was to determine whether a simplified metric, specific energy (SE), could be used to characterise a complex compressed air network. The metric was successfully applied to measure total system as well as individual compressor performance and improvement. The metric requires minimal knowledge of the CAS, compressor operation and measurement of performance characteristics. The metric could successfully identify inefficient CAS operation. Furthermore, the metric could be used to report on the success of implemented efficiency projects on the CAS

Future work should include a study on the effects of demand side interventions on the SE and how it changes when taking into account the air that reaches the end users. It can also be investigated whether the metric can be used to monitor and potentially control a CAS based on CA supply and demand matching and using the metric to improve compressors prioritisation.

Acknowledgment

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2 App. B.2: Sustainable energy technologies and assessment guide for authors

SUSTAINABLE ENERGY TECHNOLOGIES AND ASSESSMENTS
An International Journal

AUTHOR INFORMATION PACK

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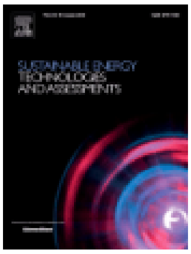

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DESCRIPTION

The world must move toward a more sustainable energy future, and the development of technologies that facilitate this for transport, heating, and power systems is crucial. This journal encourages papers on any aspect and scale of technologies for energy generation and/or utilization that decrease the impact of that production and use, from the laboratory to commercial applications.
Papers on technology development/improvement, integration, regulation, standards and policy are within the scope of the journal, as well as case studies.
Technology assessments estimating and discussing metrics such as scale of application, size and weight per unit of energy output, economics, efficiency, and state of technology development are particularly welcomed, for both individual or comparative systems.
The main fields of focus are generation, storage, and conversion; energy efficiency and distribution; and policy and economics. Energy fields include, but are not limited to, carbon capture and storage, wind, bioenergy, solar/PV, hydro, geothermal, and conventional fuels, along with system analysis, environmental issues, energy harvesting, and building design. Papers that incorporate more than one of these topics, either in a unified system or through a comparison of these fields, are encouraged.

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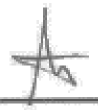
APPENDIX C. CO-AUTHOR STATEMENT

I, J.H. Marais, hereby provides consent that the articles listed below (I and II), may be used as part of William George Shaw M.Eng dissertation.

X 

J.H. Marais
Dr

I, M.J. Mathews, hereby provides consent that the articles listed below (I and II), may be used as part of William George Shaw M.Eng dissertation.

X 

M.J. Mathews
Dr

Articles:

I. W.G. Shaw, M.J. Mathews, J.H. Marais, "Holistic analysis of the effect on electricity cost when varying shift schedules according to time-of-use tariffs," *Journal of Energy in Southern Africa*, 2018.

II. W.G. Shaw, M.J. Mathews, J.H. Marais, "Using specific energy as a metric to characterise compressor system performance," *Sustainable Energy Technologies and Assessments*, 2018.