Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems

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ABSTRACT

Title: Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems

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Keywords: Compressed air systems, simplified investigation methodology, benchmarking to rank scope for improvement, quantify potential energy saving targets.

Marginal deep-level mines in South Africa are struggling due to current economic conditions. Reducing operating cost on these marginal mines will increase their profitability. Electricity is one of the fastest growing expenditures of which compressed air accounts for approximately 17% of the total electricity cost. Deep-level mine compressed air systems are often mismanaged, which results in energy wastage. Thus, energy service companies (ESCOs) have identified compressed air systems as an area with significant potential for reducing the operating costs of deep-level mines.

ESCOs have expertise in different fields to investigate, quantify and realise new energy saving initiatives. Usually, a client approaches an ESCO to examine new possible energy saving initiatives. However, due to current financial constraints, marginal mines cannot afford the service of energy savings experts. Previously, Eskom provided Integrated Demand Management (IDM) funding to motivate both ESCOs and clients to implement energy saving initiatives. However, funding for these initiatives has reduced significantly and only rewards load reduction within the Eskom evening peak period.

The problem is that reward is not guaranteed for the investment required from ESCOs during investigation periods. Therefore, ESCOs are required to take risks while investigating new potential energy saving projects. These investigations include benchmarking methods for ranking energy performances and tools for quantifying potential energy saving targets. However, it is not feasible for ESCOs to investigate all potential energy saving projects due to the constraints of existing investigation processes and reduced IDM funding.

Available benchmarking methods require multivariable data sets. These data sets are not always readily accessible or feasible to collect during the investigation phase, which could then prolong investigation periods. The first aim of this study is developing a new single-variable benchmarking method that will simplify benchmarking during investigations on deep-level mine compressed air systems.

The second aim of this study is simplifying current tools used to quantify potential energy savings. Existing approaches quantify potential energy savings with complex simulation models and detailed audits. The problem is that simulation packages are often time-consuming, and require skilled workers and multivariable data sets as inputs. This complexity adds strain to an ESCO's resources. Therefore, this study focuses on developing a practical tool that only requires power consumption to quantify potential energy savings during investigations.

As a whole, research conducted for this study further highlights a need to reduce the risks and investments required from ESCOs during investigations. The new benchmarking method and savings quantification tool were combined into an integrated investigation methodology. This integration provides a simplified high-level investigation methodology that will reduce the time, cost and resources required by ESCOs while investigating new energy saving projects. Consequently, more potential energy saving projects will be feasible for ESCOs to investigate.

The new methods and tools developed in this study were verified with available methods and tools from previous studies. These methods and tools were validated by applying them to the compressed air systems of two actual deep-level mines, which are referred to as Case Study 1 and Case Study 2. The novel benchmarking method proved successful for ranking the compressed air systems according to scope for improvement. The new practical tool to quantify potential energy savings during Eskom evening peak period was 98% accurate in Case study 1 and 87% accurate in Case Study 2.

The simplified high-level investigation methodology devlivered the required results wihtin 10 minutes with only power consumption as in input. Conventional investigation processes implemented by ESCOs used multivariable data sets, which required a minimum of 4 days in Case study 1 and 12 days in Case study 2. These case study results proved that the new investigation methodology can be used with limited resources and will improve the feasibility for ESCOs to investigate more potential energy saving initiates.

The new investigation methodology was further implemented on a holistic application to identify potential missed energy saving opportunities on 25 existing compressed air energy saving projects. As a result, it was determined that an additional saving of 82.7 MW could be realised during Eskom's evening peak period. This equates to an approximate annual cost saving of R60 million. This potential savings could contribute to the sustainability of marginal deep-level mines in South Africa.

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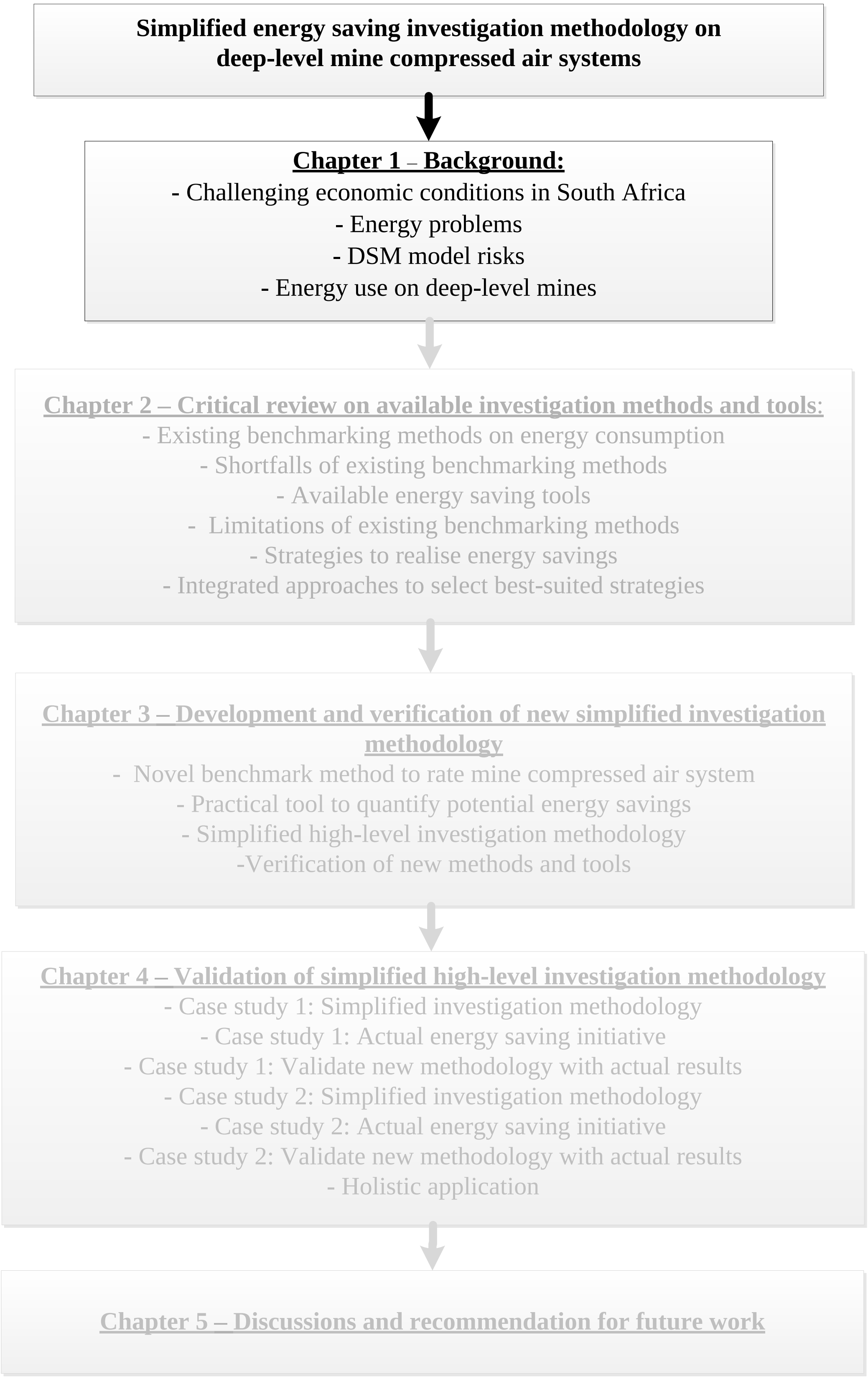
LIST OF ABBREVIATIONS

DSM	Demand-side Management
EAS	Eskom Advisory Services
EE	Energy Efficiency
ERR	Energy Reduction Ratio
ERRI	Energy Reduction Ratio Increase
ESCO	Energy Service Company
IDM	Integrated Demand Management
LC	Load Clipping
M&V	Measurement & Verification
NERSA	National Energy Regulator
SANS	South African National Standard
SCADA	Supervisory Control and Data Acquisition
PGM	Platinum Group Metals
PLC	Programmable Logic Controller
TOU	Time of Use

LIST OF SYMBOLS

GW	Gigawatt	Power
GWh	Gigawatt-hour	Energy
h	Hour	Time
kPa	Kilopascal	Pascal
kt	Kilotonne	Weight
kW	Kilowatt	Power
kWh	Kilowatt-hour	Energy
m	Metre	Head, depth or length
m^3	Cubic metre	Volume
MW	Megawatt	Power
MWh	Megawatt-hour	Energy
oz	Ounce	Weight
Pa	Pascal	Pressure

1 BACKGROUND



Simplified energy saving investigation methodology on deep-level mine compressed air systems

Chapter 1 – Background:
- Challenging economic conditions in South Africa
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- Energy use on deep-level mines

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1.1 Preamble

This introductory chapter provides a background on challenges facing the South African mining industries and energy service companies (ESCOs). The need of this study is developed based on the challenges discussed in this chapter. These challenges include current economic conditions in South Africa, energy problems, and existing demand-side management (DSM) model risks. The chapter then further discusses energy use on deep-level mines, which highlights the energy use contribution of compressed air systems.

1.2 Challenging economic conditions in South African

1.2.1 Overview

China is the world's fastest growing economy and has been responsible for approximately half of the global commodity prices since 2002. However, in 2015, China's growth reduced to its lowest in 25 years, which adversely affected global commodity prices. Reports have found that capital expenditure projects that started at the beginning of the century are now operational and increasing the supply of commodities. Large mining companies also still produce commodities, which adds to the existing oversupply [1], [2], [3], [4].

The excess supply together with the slowing demand result in a surplus of commodities. Low commodities prices could decrease to a point where revenue does not justify production any longer. Although the typical reaction for mining companies would be to reduce production, larger mining houses can continue to oversupply commodities and decrease unit costs, which will force competitors to withdraw from the market. Therefore, small or marginal mines close, mothball, sell off or downsize their mines to cut costs and prevent losses [1], [2], [3], [4].

Due to the current economic depression and low commodity prices, investors have lost confidence to invest capital. Therefore, South Africa faces numerous associated challenges, which must be solved to ensure the survival of the mining industry. Marginal mines are now looking for options that will ensure sustainability [1], [3].

Some of the world's biggest auditing firms have analysed priorities and challenges. These are disclosed in mixed reports of 31 mining companies. Among others, these challenges include labour relations, operating costs, capital management, and reliance on third parties. These challenges will be discussed further in this section [1].

1.2.2 *Labour relations*

Workers in the mining sector demand higher salaries and wages while productivity decreases. This contributes to the reduced profitability that the mining industry is currently facing. Considering platinum group metals (PGMs), the productivity per employee measured in kilogram decreased by an estimated 46% from 1999 to 2012. However, during this period, real labour cost increased 233% per kilogram of PGMs produced [5].

Figure 1 illustrates the divergence between productivity and labour cost that concerns investors [6], [7]. Productivity in the gold mining industry declined by 35%, which follows similar trends to PGMs [5].

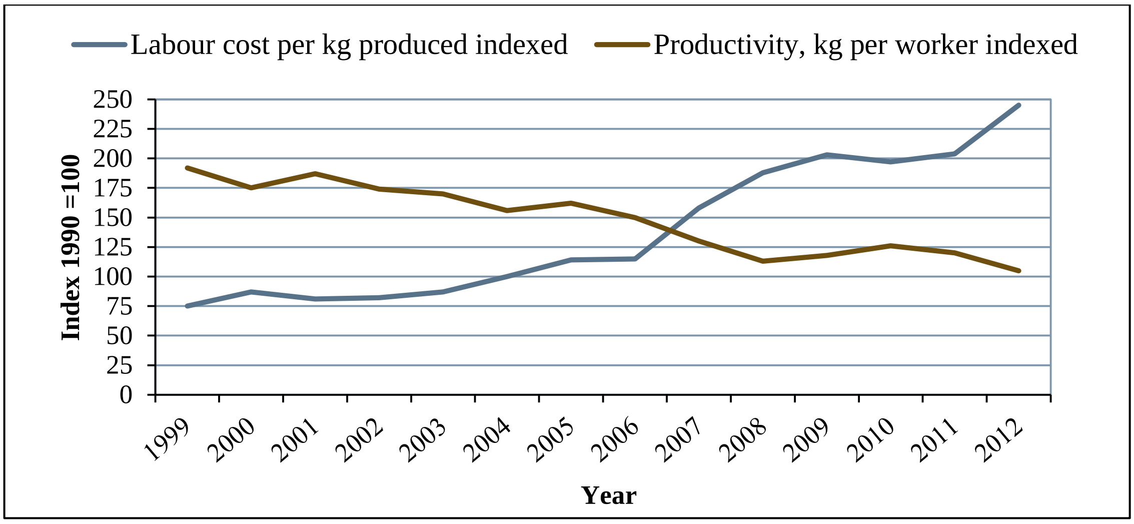


Figure 1: Divergence between labour cost and productivity (adapted from [7])

Strike action that occurred between 2012 and 2014 is one of the leading contributors to recent productivity deterioration. These strikes led to increased labour costs and decreased productivity while overhead costs still had to be covered. Strike actions, especially in the platinum industry, had adverse effects on the economy during 2014. Therefore, labour relations has a significant impact on mining profitability. Mitigation strategies for reducing this risk include ongoing wage negotiations and long-term commitments to unions [1], [8].

1.2.3 *Operating cost*

Operating costs are ever-increasing due to the rise in labour costs, consumables and utilities (water and electricity). Compared with 2015, labour cost increased by 5.4%. It remains the leading expenditure accounting for up for 40% of the total expenditure cost in 2016 (see Figure 2) [1], [4]. Consumables was the second-largest expenditure in 2016 contributing 29% of the total expenditure. Utilities, including electricity and water, was the fourth-biggest expense and accounted for 11% of the total expenditure. However, the electricity price has increased above inflation in recent years.

The Chamber of Mines joined other organisations such as the National Energy Regulator (NERSA) to limit Eskom's above-inflation price increase to 8% in 2016. Electricity is highlighted as one of the fastest growing expenditures threatening the production cost of energy-intensive mines [1], [4].

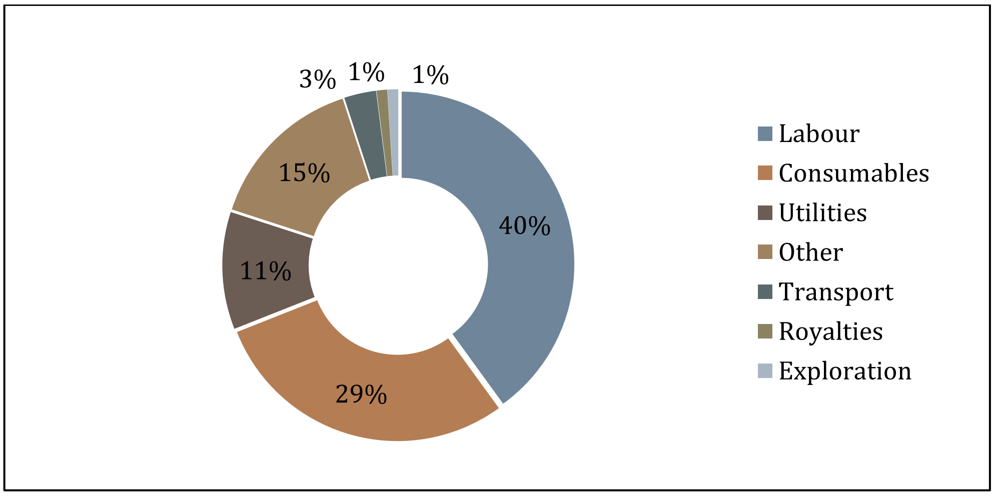


Figure 2: Breakdown of total operating costs of mining in 2016 (adapted from [1])

1.2.4 *Capital management*

Mining companies reduced their capital expenses compared with previous years. While capital expenditures decrease, lower profitability for most big mining companies resulted in less tax reliability. Companies who did not reduce their expenditures maintained their capital expenditure at a comparable level. However, lower capital expenditure generates free cash flow for improving deteriorating conditions [1], [4]. Figure 3 illustrates that due to economic conditions, mines have been shifting their focus away from capital expenditure since 2013. Capital expenditure has decreased across all commodities.

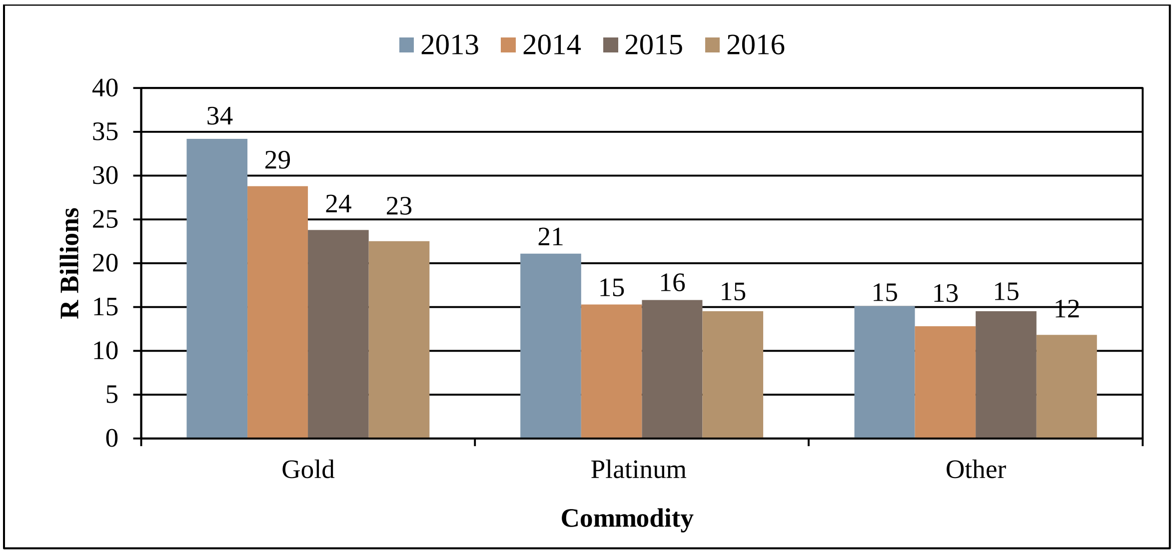


Figure 3: Capital expenditure per commodity (adapted from [1])

1.2.5 Reliance on third-party utility services

South Africa recently experienced one of the worst droughts, which was also a risk to the mining industry. Most mining operations require water for production or cooling purposes. Therefore, similar to electricity, a reduced water supply affects safety, equipment and production performances. The mining industry consumes approximately 5–8% of the total water supply in South Africa and accounts for up to 13.8% of the country's total electricity sales. Therefore, reliable utility supply remains a vital role in the mining sector [9], [10], [11], [12].

1.3 Energy problems

1.3.1 Overview

Eskom is a government-owned utility that produces an estimated 95% of South Africa's electricity. The operating costs of existing power plants and expansions have continuously increased throughout the 1970s. Instead of increasing the generation capacity, it was more feasible for private companies to improve their consumption patterns to match demand with supply. Thus, demand and supply optimisation is considered as the origin of DSM [11].

Due to mismanagement of expanding generation capacities, the electricity demand in South Africa has increased faster than the generation capacity. The reserve margin (generation buffer) in 2004 was only 7%, which was less than half of the ideal reserve margin. Unforeseen and planned maintenance contributed to the demand exceeding the supply. Therefore, load shedding has been implemented since 2008 to avoid a total blackout [11]. Figure 4 shows how the peak demand has exceeded the generation capacity between 2008 and 2013.

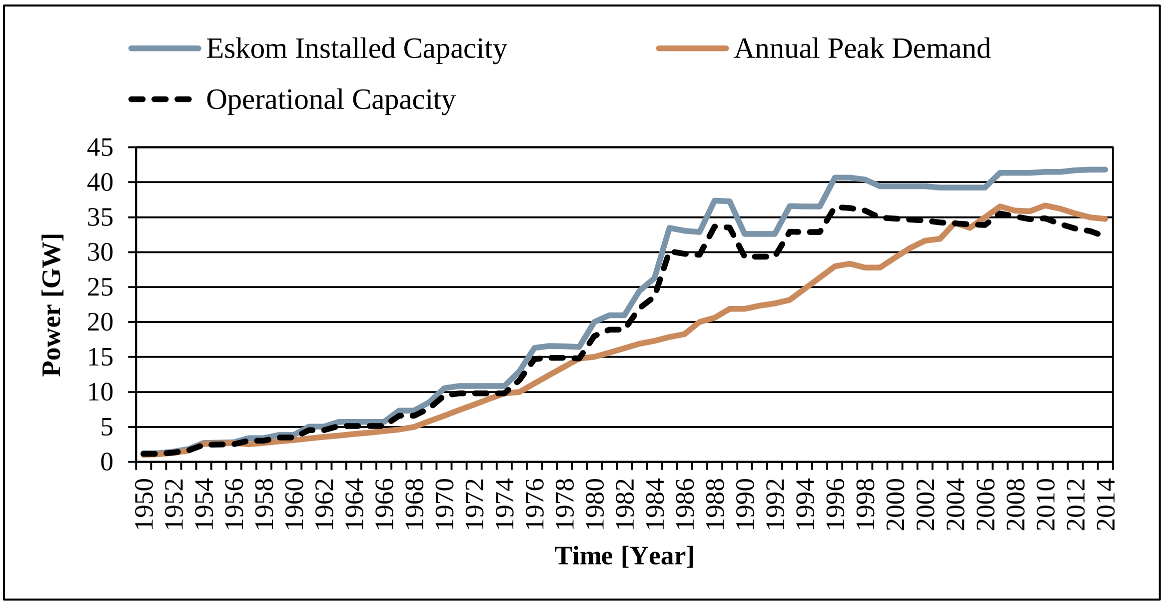


Figure 4: Demand and supply capacities from 1950 to 2013 (adapted from [11])

In early 2004, Eskom received approval from NERSA to implement DSM. Eskom was required to implement DSM as a short-term solution to match the demand and supply for electricity [13]. Various DSM measures were implemented to improve system efficiencies to change the country's energy demand patterns [11].

The DSM framework finished in 2004. However, several DSM strategies have already been initiated between the 1990s and 2004. These strategies included the time-of-use (TOU) structure and Eskom Advisory Services (EAS). The EAS provide advice to all industries on interventions to reduce energy usage and optimise energy efficiency [11], [14].

1.3.2 Methods for improving energy demand patterns

Improving efficiency is important for securing a sustainable electricity supply. However, the focus was on changing the demand pattern due to the country's power generation limitations. During 2014, Eskom struggled to supply the high demand required – particularly during winter months. Figure 5 shows how demand patterns vary between winter and summer seasons.

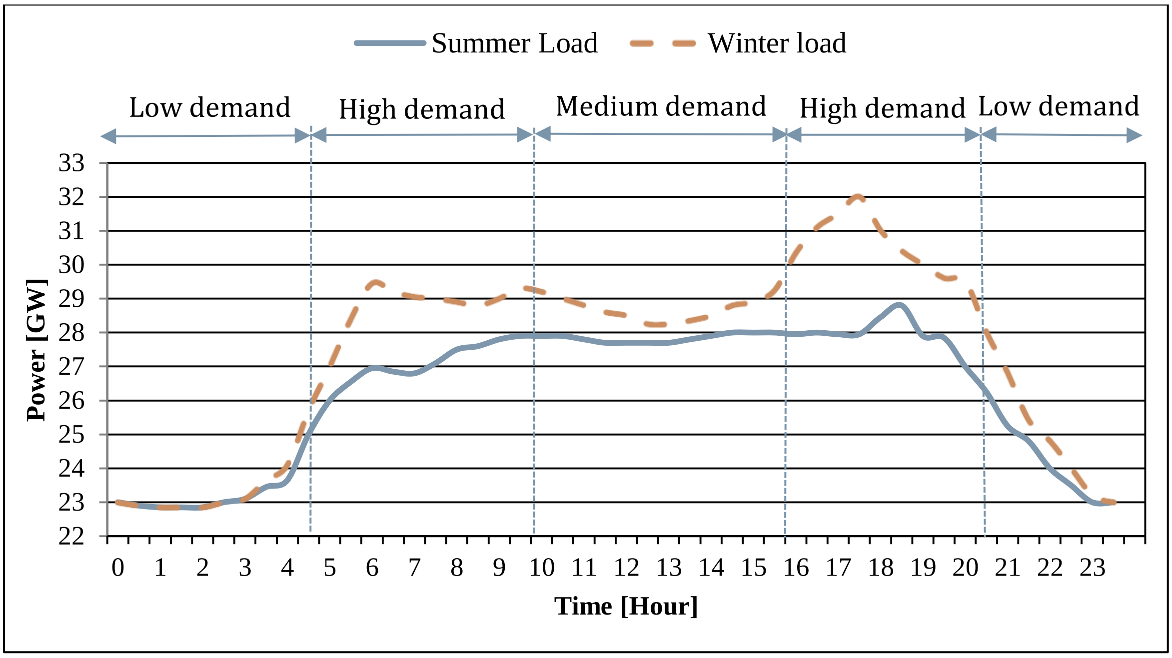


Figure 5: Demand patterns during winter and summer seasons (adapted from [15])

TOU tariff structures introduced three distinct periods including low (least expensive), medium and high-demand periods (most expensive). The purpose of the TOU structure was changing the demand patterns during certain time periods. These changing patterns accommodated Eskom's supply constraints [11], [15].

Further DSM measures were implemented to reduce energy during peak periods. These actions included energy efficiency, load shifting and load clipping initiatives. Energy efficiency initiatives concentrate on reducing the average electricity use throughout a day without affecting production.

Figure 6 illustrates the impact of an energy efficiency initiative on a power consumption baseline.

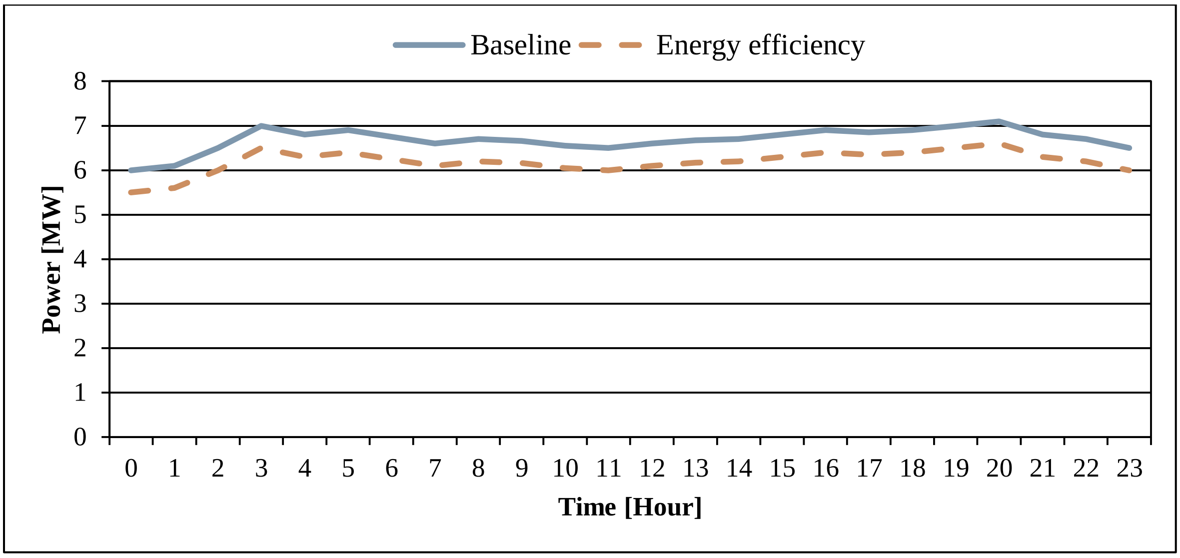


Figure 6: An energy efficiency impact on an energy system (adapted from [15])

Load shifting initiatives focus on moving energy demand patterns away from the high-demand periods. This energy demand is then distributed to less expensive demand periods. Figure 7 shows the impact of a typical load shifting initiative on a power use baseline.

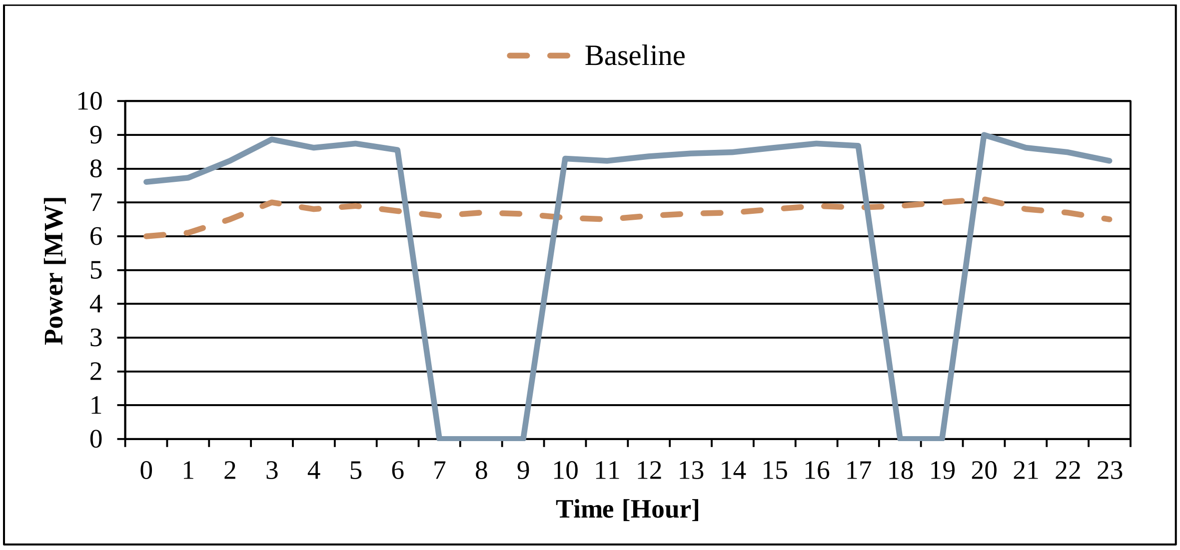


Figure 7: A load shifting initiative impact on an energy system (adapted from [15])

Peak clipping is similar to load shifting. The difference is that the energy demand moved from high-demand periods is not redistributed to less expensive periods. Peak clipping initiatives should, however, still not affect production. Figure 8 shows an example of a peak clipping impact on an energy consumption baseline.

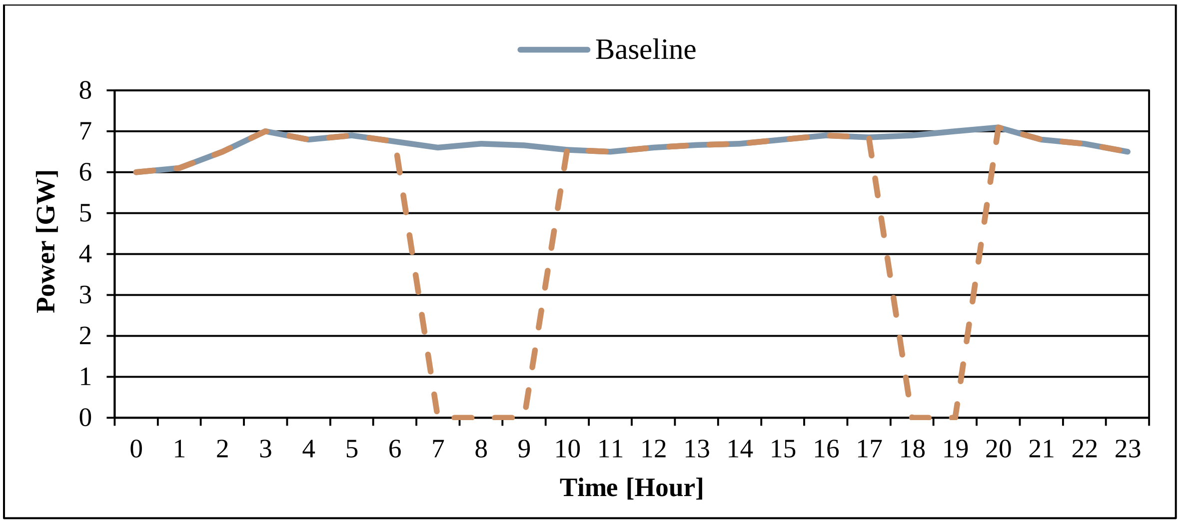


Figure 8: A peak clipping initiative impact on an energy system (adapted from [15])

DSM saving initiatives have various benefits on social, economic and environmental levels. Less carbon dioxide emissions are generated by reducing energy use without affecting production. Load shifting initiatives save electricity cost, but the power consumption remains the same. Energy efficiency and peak clipping projects are therefore preferable from an environmental perspective.

1.3.3 South African ESCOs

ESCOs together with major energy consumers investigate the feasibility of implementing DSM initiatives. If an ESCO or consumer finds a DSM initiative worthwhile, then proposals are submitted to Eskom who funds these initiatives. If Eskom finds the proposal feasible, Eskom's Integrated Demand Management (IDM) programme provides funding to clients [15], [16]. These DSM models are discussed further in Section 1.4. Table 1 lists typical industrial DSM projects implemented by ESCOs.

Table 1: Typical industrial DSM projects implemented (adapted from [11])

LOAD SHIFTING INITIATIVES	PEAK CLIPPING INITIATIVES	ENERGY EFFICIENCY INITIATIVES
• Pump, mill and winder scheduling. • Industrial refrigeration plant and ventilation system load management.	• Compressor off-loading and stopping. • Pump, mill and industrial furnace stopping.	• Variable speed drive control. • Efficient lighting. • Water demand control. • Compressed air demand control.

Eskom budgeted R340 billion to expand their generation capacity by 17 GW from 2005 to 2019. This electricity supply increase, therefore, has an estimated cost of R20 million per megawatt. A typical DSM initiative implementation had an approximate cost of R5.25 million per megawatt. The high cost to upgrade generation capacity is thus approximately four times more expensive than demand reduction through DSM initiatives [17].

One of the primary objectives for Eskom was delaying the need for increased generation capacity. DSM initiatives aimed to reduce the total power demand with 4 225 MW over a period of 20 years. This power reduction equates to the generation capacity of large coal-fired power stations. However, there is still potential for reducing unnecessary electricity usage on high energy demand systems [15], [12]. The demand reduction realised during high-demand periods from 2005 to 2014 is shown in Figure 9.

Figure 9 shows the savings target which was set from 2005 to 2014 to reduce power demand. The power reduction target of 4 225 MW was realised approximately ten years before the expected date. However, Eskom spent a further R1.36 billion on DSM initiatives during the financial year of 2013/2014. The continuous expenditure indicates that Eskom is still interested in driving DSM programmes. However, it was made public in 2013 that Eskom had a shortfall of R7.9 billion for its IDM funding [11], [18], [19].

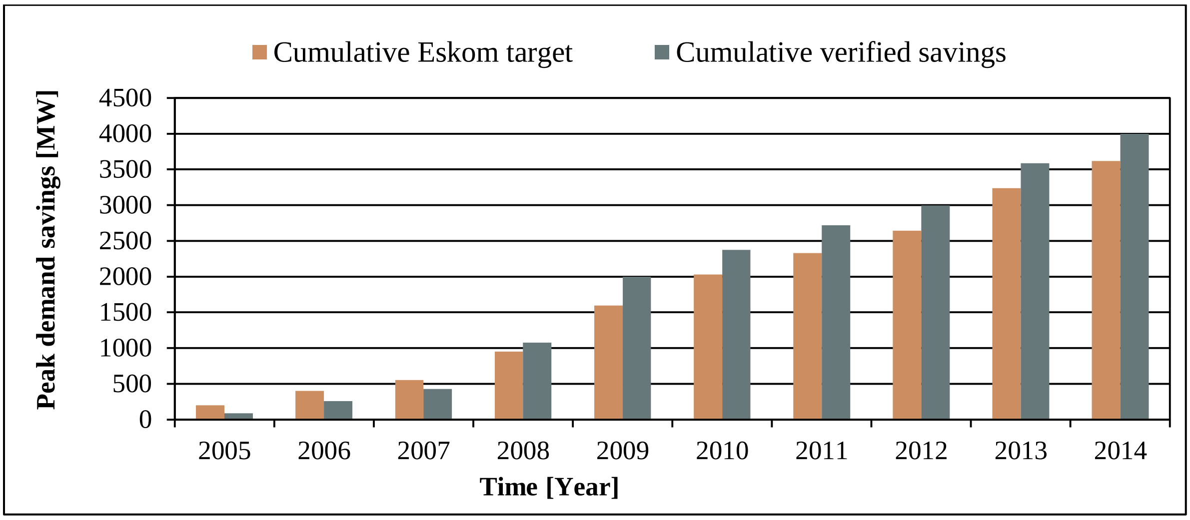


Figure 9: Cumulative savings through DSM initiatives (adapted from [20])

No funding has been available from October 2013 to January 2015 for new projects. Therefore, no new projects have been implemented. Eskom then restarted IDM funding in February 2015. However, the funding available for DSM projects has significantly reduced.

Reducing the energy demand of industries requires investigations, implementation and commissioning processes. These procedures are costly but remained feasible with funding initiatives [6], [16]. ESCOs had to apply for necessary funding to implement the ESCO DSM models introduced by Eskom [21].

1.4 DSM model risks

1.4.1 Overview

Without sufficient funding, it makes it challenging for ESCOs to implement DSM initiatives. Funding models are available to motivate participation in these types of initiative. Well-known funding models include the shared savings model and the guaranteed savings model.

For a shared savings model, ESCOs often fund the project and then claim a percentage of the savings from Eskom. In the shared savings model, an ESCO is rewarded for achieving savings greater than the target. However, with the guaranteed savings model, ESCOs are paid for savings that they guarantee. Overperformance in this model can be claimed and shared between the client and ESCO. Thus, for both the shared savings and guaranteed savings models, ESCOs are rewarded for overperformance [21], [22], [23].

Eskom also introduced a project-based model where the ESCO is responsible for the contract until completion of the performance assessment. Then, the project is handed over to the client to maintain. With this model, ESCOs do not receive compensation for overperformance. However, the ESCO has a minimal risk during the implementation and performance assessment periods of these projects [21], [22], [23].

1.4.2 The project-based model

The project-based model was unique to South Africa and functioned satisfactorily. The reason for the success of this model was because the client needed to reduce expensive electricity cost while Eskom had to reduce the demand on the national grid [21], [22], [23].

As previously mentioned, ESCOs implemented Eskom's DSM models with a project-based approach. The approach is due to the project nature of DSM models. Since the initiation of the IDM programmes up until the middle of 2015, the following DSM project phases have been applied to realise energy savings [21], [24], [25]:

1. Investigations
2. Proposal approval
3. Implementation
4. Performance assessment

The goal and risks identified in the project phases of the project-based IDM model are further discussed in this section. These aims and risks have been determined from previous research of over 100 IDM projects [21].

Investigation phase

The project-based model investigation phase had two goals, namely, finding potential clients and finding new project opportunities. Clients were familiar with the DSM and IDM funding models, and the energy expertise of ESCOs. Due to mismanagement of some cases, clients stole the intellectual property of ESCOs and implemented IDM projects themselves. This led to ESCOs not receiving return on investment while investigating and developing projects to realise energy savings [21].

ESCOs initially found simulations and validation of potential IDM projects challenging during the initial investigation phase. Therefore, ESCOs could not always quantify potential savings, which led to IDM projects either under- or overperforming. Eskom did not reward overperformance in the project-based IDM model. But, ESCOs were penalised for underperformance. The model thus put ESCOs at risk of losing funding [21].

Independent measurement and verification (M&V) teams were used by Eskom to verify the investigations of the ESCOs. The M&V team had to approve the baseline development during the investigation phase. Section 1.4.4 further discusses M&V responsibilities and processes. During investigations, time and investment were lost. Lost time was due to cases where data and information were either not readily accessible or the data quality was inadequate.

Revisits were necessary for poor data sets, which complicated the findings reports and proposal documents [21]. In summary, the research found that the investigation phase of the previous project-based IDM model posed risk for ESCOs. These risks included [21]:

- Unprotected intellectual property during marketing and poor documentation, potentially leading to lost funding.
- Inadequate information which leads to poor validation and proposed project savings.

Project approval phase

Proposals were submitted in the project approval phase to apply for funding approval. These proposals were assessed against financial, legal, technical and commercial criteria. If all criteria were satisfied, projects were approved for funding [24], [26]. The client made decisions during the proposal phase, while ESCOs were involved during contract negotiations and sign-off.

The IDM funding department determined if proposals were worth the investment. In some cases, a proposal was disqualified [21]. The ESCO then lost the potential finance and time that have been invested. However, the ESCO could resubmit the proposal after complying. Eskom only accepted a limited number of proposals although numerous proposals were submitted from various ESCOs. If an ESCO resubmitted a proposal, the proposal could still be rejected due to a backlog of submissions. Therefore, it was possible that resubmitted proposals were only evaluated during the next round of applications [26].

The potential delays highlighted the importance of submitting proposals with the correct information to satisfy requirements. In summary, ESCOs were at risk during the previous project-based IDM model proposal phase in the sense that IDM funding disqualified inadequate or incomplete proposals. Previous research indicated that incomplete data sets contributed to inadequate proposals [21], [26].

Implementation phase

The implementation phase initiated after contracts had been signed based on the proposals submitted for funding. The main advantage of the previous project-based IDM model implementation phase was that a portion of the contracted value was available for ESCOs to use as capital layout. Limited options were available to put the project at risk for termination. Termination of the contract would, however, risk a financial loss for ESCOs. Previous research identified typical shortages during the implementation phase. These shortages included [21]:

- Good document control and communication
- Quality and resource management
- Product and service management
- Consistent contract compliance (B-BBEEE and SD&L requirements)

Performance assessment phase

The previous project-based IDM model performance evaluation required the ESCO to realise a minimum of 90% of the targeted savings submitted in proposals. This performance then had to be sustained over a period of three months. The M&V team played a key role in approving the savings achieved by the ESCOs in order to release the funding (reward).

The ESCO was awarded the full contracted value only once the performance assessment was completed. The client was then responsible for maintaining the performance for a predetermined period. It was found that several clients did not sustain the performance required from Eskom after handover. The shortfalls identified in the performance assessment phase included both delayed turnaround times and poor performance management and monitoring [21], [27].

1.4.3 Changes to Eskom IDM funding model

In 2015, Eskom introduced new M&V guidelines for implementing new projects with new project-based models. The guidelines had two primary concerns. The first concern was Eskom’s financial constraints regarding IDM funding. As a result, the contracted value for DSM projects reduced significantly. The second concern was that clients were not maintaining performance as required after handover. The new IDM model, therefore, focused on shifting the risks and responsibilities to the ESCO over the full contracted period [6], [21].

Eskom developed the model based on performance contracting, which originated from the previous project-based model. Therefore, ESCOs are paid based on project performance over the contracted period. Unlike the old IDM model, payments to ESCOs are now related to project implementation and performance completion. This new payment process has a significant impact on the cash flow for new projects [21].

Although the budgets and cash flow are smaller for new projects, Eskom and clients expect similar saving impacts than achieved with the older IDM models. Therefore, it is not feasible for ESCOs to risk the input required to investigate and submit proposals for all projects. There is a need to reduce the risks of ESCOs during the investigation phase of projects. Reducing the risk and input required could lead to more project implementations.

The new IDM model works as follows [6], [28]:

- Only savings during Eskom's evening peak period (18:00–20:00) are rewarded.
- The ESCO must sustain the project for a contracted period of 36 months. The contracted period consists of 12 × three-month performance assessment periods.
- Up to 30% of the contracted value is paid after the first three-month performance assessment.
- The remaining 70% is paid over the remainder of the 11 × three-month performance assessments.
- Demand reduction during the evening peak period must be larger or equal to 500 kW, which must be achieved based on the Megaflex TOU tariff.
- Eskom requires the project to be implemented within six months after acceptance.
- ESCOs are not rewarded for overperformance. However, Eskom may claim underperformance.

1.4.4 M&V challenges

An M&V team is an independent third party appointed by Eskom to measure and verify the savings claimed by ESCOs. M&V is a crucial part of the DSM project life cycle, which provides confidence to approve the savings claimed by ESCOs. This section discusses the challenges experienced as a result of M&V processes.

M&V responsibilities

M&V teams have to quantify savings achieved independently and objectively over the contracted period of IDM projects. The work of these teams is governed by the South African National Standard (SANS) 50010 [29], [30]. The risks involved for ESCOs during the M&V process include modelling errors due to poor data quality or inadequate measurements. M&V teams rely on ESCOs to supply the required data sets for developing M&V models and reports [31]. The reporting performance of M&V teams has significant impact on the success of IDM projects.

M&V management

M&V requirements can demand several resources from ESCOs to supply adequate data within given periods. These requests can vary from data collection to document sign-off. A large number of an ESCO's resources is needed when several projects are investigated and implemented in parallel.

Several project engineers and M&V consultants are required during baseline development and performance assessment. Therefore, time and input are at risk if ESCOs do not reduce M&V process turnaround times. ESCOs often implement measures to reduce the turnaround time of M&V requests. As a result, by managing M&V requests, less time is needed to investigate and apply DSM projects. This reduces the risks for ESCOs to miss deadlines for project proposals [21], [30].

Data acquisition

The first relevant data set required from M&V teams is electricity consumption, which is needed to develop energy use baselines. These baselines are used as references for performance tracking [32]. Electricity use is found to be the most readily accessible and available data. Electricity consumption data can be logged and downloaded from a client's site. Eskom bills can also be used to quantify electricity use. Contract placements may only commence once baselines have been signed off. If contract placement is delayed, the ESCO risks losing the DSM project contract with Eskom [21], [27], [33].

Baseline development

A baseline represents energy use on an energy system before ESCOs intervention. The impact of an ESCOs intervention is measured against the baseline to quantify the savings impact. These baselines may require scaling methods to accommodate changes in operation. These methods vary according to project types, the nature of the system, or the technology involved [31], [34].

Performance assessment and tracking

After baseline approvals and project implementation, the impact of the energy saving initiatives is measured during performance assessment periods. It is important for M&V teams to have access to the data required during the performance assessment phase. Delayed or unreliable data collection methods risk ESCOs losing savings achieved during performance assessment periods.

The cash flow and payments to ESCOs depend on the performance reports [21], [32]. It is important that the data is accessible for ESCOs to supply the data to M&V teams during performance assessments. The M&V team reports monthly although the performance periods can vary between projects. M&V teams provide performance certificates based on the average performance at the end of the assessments [21], [32]. The new ESCO DSM model requires M&V teams to provide performance tracking reports in three-month intervals.

1.5 Energy use in deep-level mines

Most existing mines in South Africa were developed when energy efficiency was not a requirement as it is today. Different mine operations were also overdesigned to accommodate future expansions [35]. Gold mines are the largest energy consumers accounting for 47% of the total energy consumed by the mining industry. Platinum mines are second with a consumption of 33%. Other mines only consume 20% of the total demand [36]. Figure 10 illustrates the energy demand breakdown within a typical deep-level mine.

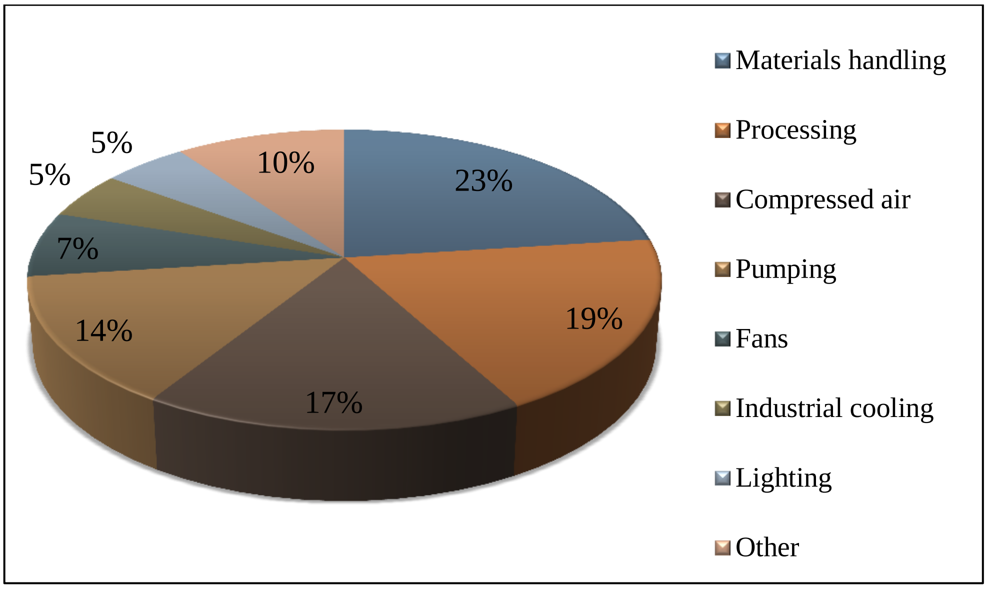


Figure 10: Energy consumption breakdown within a general deep-level mine (adapted from [36])

Among South African deep-level mines, compressed air is predominantly used to extract ore during production [37]. Energy-intensive compressors transfer air through extensive pipe networks. Transferring compressed air through pipe networks is considered to be one of the most expensive methods for distributing energy within the mining industry [38]. Energy saving companies have identified deep-level mine compressed air systems as an area with significant potential for implementing energy saving initiatives [39].

These compressed air systems consist of several compressors, which can be operated manually by an operator or automatically by a programmable logic controller (PLC). The number of compressors can vary depending on the air demand volume. The size of these compressors can be up to 15 MW with a combined daily energy demand of 883 MWh on a normal working day [17].

Thus, compressed air networks are responsible for approximately 17% of the total energy demand within the mining industry [36]. Electricity cost should be managed more efficiently as it is one of the fastest growing expenditures [6]. This study focuses on enabling ESCOs to optimise compressed air networks of deep-level mines to save operating costs while relieving the generation demand of Eskom.

The energy use profile in Figure 11 shows the power consumption profile of compressor combinations during normal mining operations. The normal operational day can be categorised into two main shifts known as drilling and non-drilling shifts. Drilling shifts typically have the highest compressed air and power consumption demand.

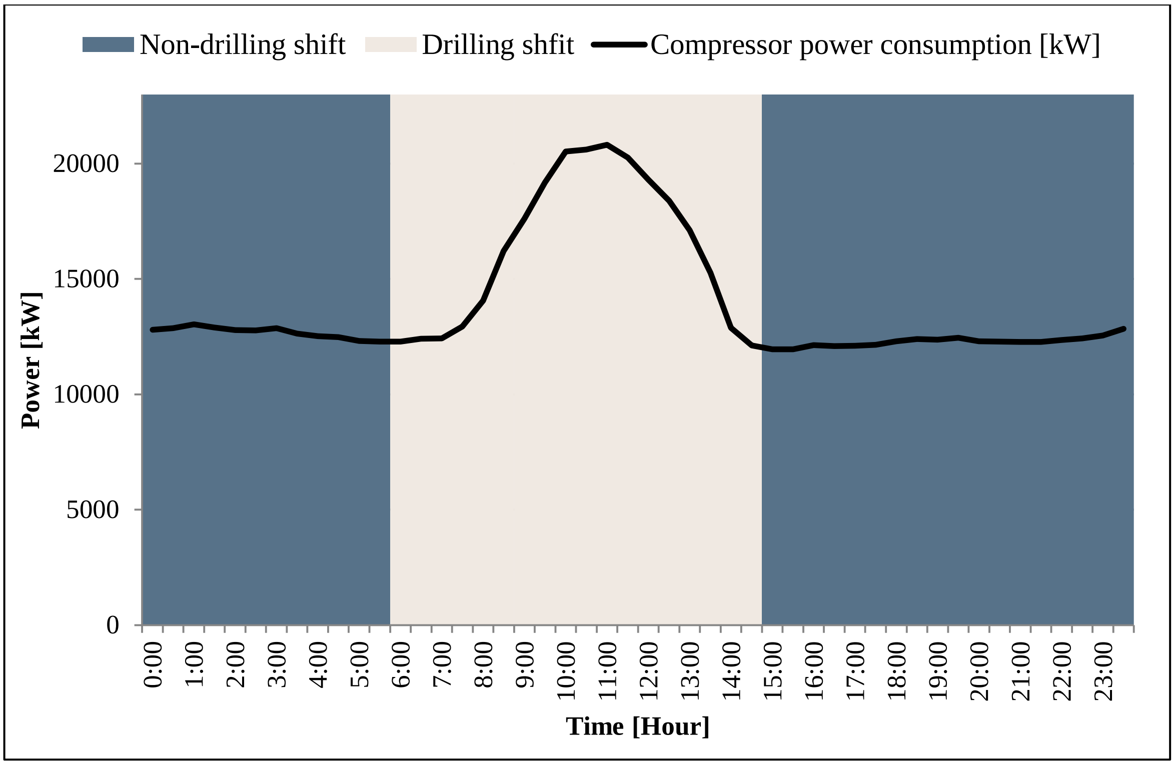


Figure 11: Typical power consumption profile during normal mining operations

Figure 12 illustrates an example of a typical deep-level mine's compressed air distribution network. This mine has three compressors feeding into a pipe network. The pipe network on the surface is fed from energy-intensive compressors to sustain the required system pressures. The sizes of these pipe networks range from 150 mm to 700 mm with a maximum length of 40 km [17]. The flow rate and pressure required by end users vary. These users are located either on surface or underground.

Marais, Cilliers and Bredenkamp provided a pressure and flow demand summary of general end users during mining operations [17], [40], [41]. During a normal operational day, a mining shift consists of a non-drilling and a drilling shift. Compressed air is also used on the surface throughout a typical production day.

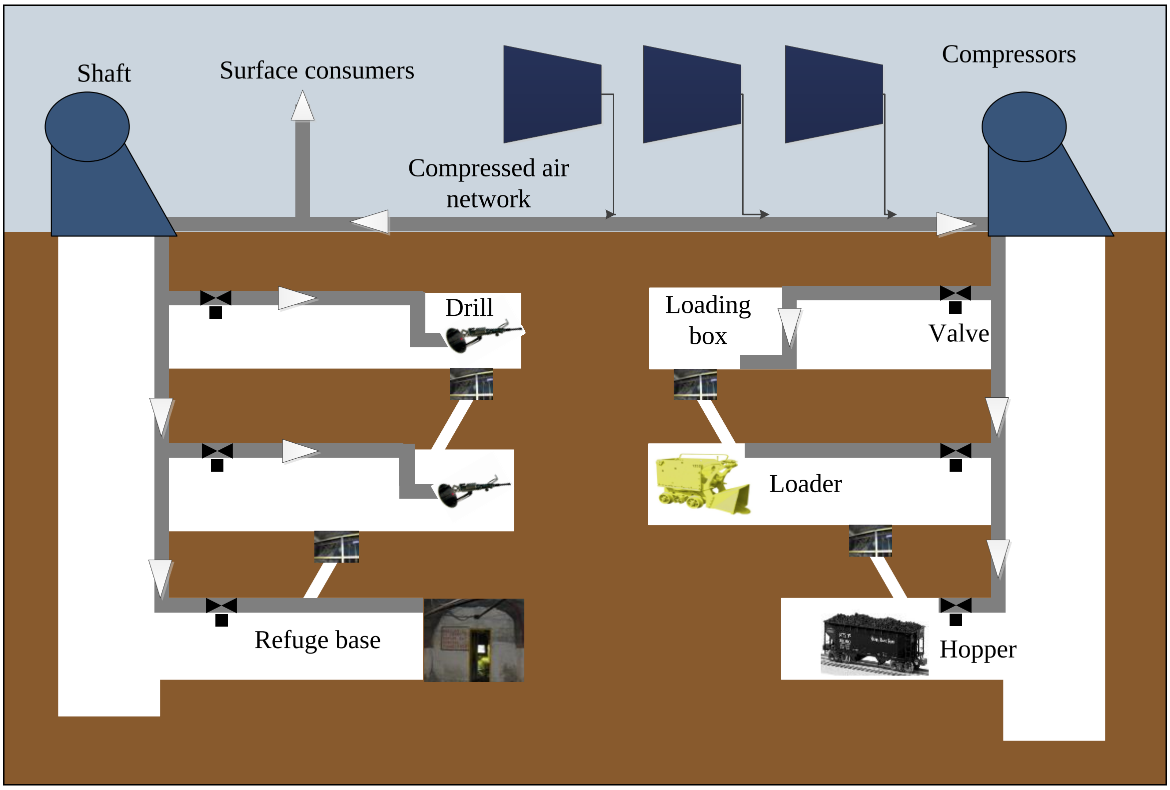


Figure 12: Illustration of a compressed air system and typical end users

Table 2 shows the usual end users on the surface. Process plants are the main compressed air users on the surface, with an average pressure demand between 420 kPa and 500 kPa. Pneumatic actuators and control valves are the lowest air users, although they require high pressures between 350 kPa and 600 kPa [40].

Table 2: Compressed air users on the surface (adapted from [40])

OPERATIONS	PROCESS PLANTS	WORKSHOPS	CHUTES AND DOORS	OTHER OPERATIONS
Purpose	Agitation to facilitate ore recovery by releasing air into large storage chambers.	Pneumatic tools are used to manufacture or repair new parts and equipment.	Ore moves to designated areas by using automatic chutes or doors.	Pneumatic actuators on surface valves, control systems and other instrumentation use compressed air.
Flow demand [m^3/h]	±2 520	±101	±504	–
Pressure demand [kPa]	±420–500	±200–250	±350–600	±350–600
Shift	Throughout day.	Throughout day.	Throughout day.	Throughout day.

Drilling shifts account for most of the compressed air usage underground. The main end users during drilling shift are rock drills, rock breakers and loaders as shown in Table 3. It is vital that the air pressures are above low limits during drilling shifts to avoid production losses. During the drilling shift, the majority of mineworkers are active underground.

Table 3: Underground air users during drilling shifts to remove and load ore (adapted from [40])

OPERATIONS	ROCK DRILLS	ROCK BREAKERS	LOADERS
Purpose	Pneumatic drills are used to create holes wherein explosives are planted. The explosions then release the ore from the rock faces.	After the ore and waste rock release from rock faces, large pneumatic breakers are used to reduce the rock and ore to manageable sizes.	Pneumatic loaders are used as front loaders to load the manageable size waste rock and ore into hoppers.
Flow demand [m^3/h]	±1 512	±1 008	±1 008
Pressure demand [kPa]	±400–620	±450	±550
Shift	Drilling shift.	Non-drilling shift.	Throughout day.

Agitators, refuge bases, blowers, open-ended pipes and other pneumatic actuated valves also use compressed air underground (see Table 4). These users form part of general mining operations found underground. Refuge bays are well-known as safety precautions underground. These bays require minimal flow and pressure at all times. Agitators optimise dewatering systems that operate throughout the day to prevent flooding [37], [41], [42], [43].

Table 4: Controllers and ventilation

OPERATION	AGITATORS	REFUGE BASIS	BLOWERS	OTHER
Purpose	Agitation ensures that the mud and particles can move through the dewatering pumping systems in a homogenous form.	Refuge bases protect a chamber and supply fresh air to underground workers during emergencies.	Blowers distribute fresh and cool air to underground mineworkers at operation points.	Pneumatic actuators on underground valves, control systems and other instrumentation use compressed air.
Flow demand [m^3/h]	±1 692	±5.04 per person	±327.6	–
Pressure demand [kPa]	±400	±200–300	±350–620	±350–600
Shift	Throughout day.	Throughout day.	Drilling shifts.	Throughout day.

Unwanted end users such as illegal mining and leaks are common in South African mines (see Table 5). Leaks are the largest contributor to air wastage and unnecessary energy use. Open-ended pipes are used for more ventilation or cleaning new expansions. This unregulated consumption leads to unwanted and irregular compressed air demands. As a result, more energy is required to sustain the flow and pressure demand [37], [41], [42], [43].

Table 5: Unwanted compressed air users on surface and underground (adapted from [40])

OPERATION	LEAKS	ILLEGAL MINING	OPEN-ENDED PIPES
Reason	Leaks occur at joints of pipe sections due to deterioration of gaskets. Improper pipe repair and unattended valves also contribute to overall leaks.	Illegal miners access mining levels through closed shafts and ventilation passes. Open-ended pipes and rock drills.	Open-ended pipes are used to clean newly develop sections throughout underground mining levels.
Flow demand [m^3/h]	Only limited to specific compressed air supply.	Only limited to specific compressed air supply.	Only limited to specific compressed air supply.
Pressure demand [kPa]	Only limited to specific compressed air supply.	Only limited to specific compressed air supply.	Only limited to specific compressed air supply.
Shift	Throughout day.	Throughout day.	Occasionally.

The combination of all the end users shown in Table 2 to Table 5 contributes to the total air demand. The air supply increases or decreases according to air demand, which relates to different mining shifts. Figure 11 illustrated how the power demand typically varies throughout a normal operational day to supply the required compressed air demand. The energy demand profile normally represents a bell-curved shape.

Extensive investigations are required to determine the feasibility and potential impact of various energy saving initiatives on specific compressed air power consumption profiles. Current processes used during an investigation phase of energy saving initiatives include the following [12], [17], [33], [44]:

- Benchmarking to create awareness
- Tools to quantify potential energy saving targets

These methods and tools are costly, time-consuming and require skilled labour. Thus, a simplified high-level investigation methodology is needed to rank compressed air system performances and quantify potential energy savings. To realise available savings on compressed air networks, both the supply and demand of compressed air have to be optimised. These optimisation interventions entail installing new technology or upgrading outdated technology. The upgraded equipment and optimisation interventions directly or indirectly affect the whole mining operation [37].

Supply-side interventions reduce oversupply, which leads to decreased operation cost. Demand-side interventions are used to eliminate unwanted demand. Although several strategies are available for optimising compressed air networks, it can be difficult to determine which interventions should be implemented. These interventions vary depending on implementation periods, implementation costs and payback periods [37].

Compressed air networks are complicated and their optimisation is often misunderstood [45]. Previous research indicated that most mine personnel responsible for compressed air networks are not fully knowledgeable. It is known that more than one person is responsible for the compressed air networks due to the variety of responsibilities and complications. Therefore, end users are customarily not aware of the energy cost of providing compressed [17].

The main goal within the mining environment is production. However, mismanaged energy consumers contribute to increased production cost and less profit. Often a person without extensive knowledge is appointed by management to save energy on deep-level mine compressed air systems. Unfit appointment of responsible personnel could result in the implementation of energy saving projects that do not achieve the expected savings [17]. This highlights the need for energy experts to reduce the mismanagement of energy consumption.

1.6 **Research objectives**

Energy systems are constrained due to a combination of inefficient systems and social and environmental challenges. The South African mining industry is energy intensive, which magnifies the importance of optimising energy efficiency. Current economic conditions limit the development and implementation of new energy innovations. Compressed air systems have been identified as a large contributor to the total electricity expense within deep-level mines. ESCOs identified this utility as an area with large potential for energy optimisation due to known wastages.

However, due to reduced IDM funding rewards as well as marginal mines that cannot afford energy experts, ESCOs are required to take risks during the investigation phase of new energy saving projects. Thus, considering the complexity and the resources required for investigating new energy saving projects on deep-level mine compressed air systems, it is not feasible for ESCOs to investigate all projects.

This study focuses on reducing the risks and resources required from ESCOs to investigate potential energy saving initiatives on deep-level mine compressed air systems. The first objective of this study is developing simplified methods and tools to be used during the investigation phase of new energy saving initiatives.

The second objective of this study is combining the simplified methods and tools developed for the first objective to deliver a new integrated investigation methodology. The new investigation methodology will enable ESCOs to minimise risk and use of resources during investigations on deep-level mine compressed air systems.. The schematic in Figure 13 illustrates the research objectives.

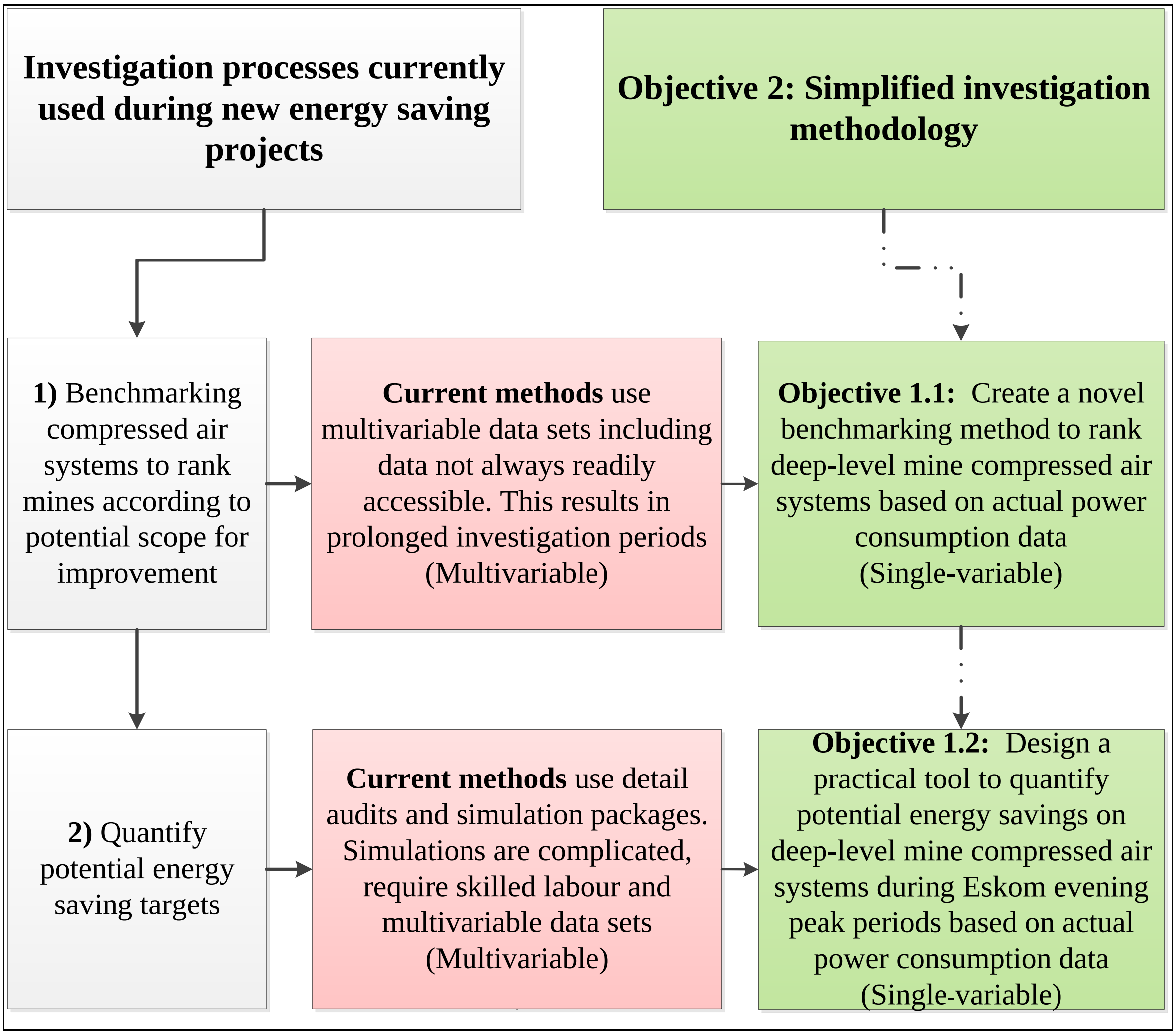


Figure 13: Schematic illustration of study objectives

Current benchmarking methods use multivariable data sets, which include data that are not always readily available. If the necessary data for current benchmarking methods is not available, extensive audits and investigations are required. Acquiring this necessary data can be time-consuming and resource intensive, which leads to prolonged investigation periods. A single-variable benchmarking method will enable ESCOs to rank the performance of compressed air systems from different mines in South Africa with only power consumption data as an input. Through this knowledge, ESCOs will be aware of the potential scope for improvement on different compressed air systems

Existing tools for quantifying potential energy savings involve detailed audits and complex simulations that are time consuming, and require skilled labour and multivariable data sets that are not always readily available. Current IDM models only reward savings within Eskom's evening peak periods. A single-variable tool that focuses on load reduction within Eskom's evening peak period will allow ESCOs to quantify potential savings that could be rewarded by IDM models. With the new tool, ESCOs will be aware of the expected energy savings target. Should the potential scope and savings target be worthwhile, further detailed investigations can be done to realise the available savings.

1.7 Novel contributions of study

1.7.1 Contribution 1

A novel benchmarking method for ranking compressed air systems based on actual energy use data

How is benchmarking presently done?

Several studies have used benchmarking to rank mine performances and to create awareness on mismanagement of electricity. During an investigation phase for potential energy saving projects, mine energy systems are ranked according to scope for improvement. Available benchmarking methods use historical multivariable data sets to identify the efficiency of compressed air systems.

Why are the current methods insufficient?

Not all mines have the required data sets readily accessible to develop available benchmarking models during a given period of investigations. Obtaining available data sets from the site is not always practical or feasible. Data acquisition for benchmarking can be resource-intensive and time-consuming.

What needs to be done?

A need exists to develop a simplified single-variable benchmarking method to compare performance ratings of compressed air systems. This method should use power consumption as a single-variable input, which is primarily available from most deep-level mines.

How does this study solve the problem?

This new simplified single-variable method will reduce risk and resources required from ESCOs during investigations to benchmark compressed air systems according to scope for improvement.

1.7.2 Contribution 2

Practical tool for quantifying potential energy saving targets on compressed air systems during Eskom's evening peak period

How is potential energy savings currently determined?

Available funding initiatives reward clients for load reduction during Eskom's evening peak periods. Detailed audits and complex simulation packages are currently used to quantify potential energy saving targets during Eskom peak periods.

Why are the current methods insufficient?

The challenge is that simulation packages are complicated, time-consuming and require multivariable data sets. These data sets are not readily available from most mines during investigations. Prolonged investigation periods and inaccurate saving estimations from ESCOs negatively affect the viability of potential energy saving projects.

What needs to be done?

A practical and time-efficient tool is required to quantify potential energy savings with limited resources. The new tool should use power consumption as a single-variable input to quantify potential savings during Eskom's evening peak period with acceptable accuracy.

How does this study solve the problem?

The new practical tool will enable ESCOs to quantify potential energy savings with readily accessible data from compressed air systems within limited time and acceptable accuracy. This will simplify the complex and time-consuming methods currently used. As a result, the risks and resources required from ESCOs to predict saving targets for new IDM projects will be minimised. Should the potential savings target be worthwhile, further detailed investigations can be conducted for confirmation.

1.7.3 Contribution 3

Simplified high-level investigation methodology based on actual energy use data

Problem statement

Due to reduced IDM funding as well as marginal mines that cannot afford energy experts, ESCOs are required to take risks during the investigation phase of new energy saving projects. Considering the time and intensive resources required for existing investigation methodologies, it is not feasible for ESCOs to investigate all potential energy saving projects.

How are investigations processes currently done?

Existing investigation methodologies comprises of tedious audits and the use of time consuming simulations.

Why are the current methods insufficient?

Available methods and tools used to investigate potential energy saving projects are time consuming, complex and require multivariable data sets, which are not available during all investigations. This could prolong normal investigation processes, which negatively impacts the feasibility of new project investigations.

What needs to be done?

A new simplified high-level investigation methodology must be developed to reduce the risks, time and resources required from ESCOs to investigate new energy saving projects on compressed air systems.

How does this study solve the problem?

The new investigation methodology developed in this study reduces the time and resources needed for investigations. This approach improves the feasibility for ESCOs to investigate more potential energy saving projects.

1.8 Study outline

Chapter 1 – Introduction

This chapter introduced and discussed several elements as background to this study. The severity of financial constraints and energy use of compressed air systems on deep-level mines were considered. The risks and input required from ESCOs to investigate potential energy saving initiatives were reviewed to identify the need for the study. The novel contributions of this study were formulated based on the shortfalls identified from the background in Chapter 1 and critical review of Chapter 2. These contributions are used as solutions to address the needs defined in both Chapter 1 and Chapter 2.

Chapter 2 – Critical review

This chapter critically examines relevant elements of this study. The review includes existing benchmarking methods used to rank system performances and tools used to quantify potential energy saving targets. The shortfalls identified in the critical review of Chapter 2 are used to develop the novel contributions discussed in Chapter 1.

Chapter 3 – Methodology and verification

The first phase of the methodology chapter develops a novel simplified benchmarking method for ranking deep-level mine compressed air systems. This method rates a compressed air system according to the potential scope for improvement. The second phase of this chapter creates a practical tool for quantifying potential energy savings during Eskom's evening peak period. All the methodologies mentioned above are developed using actual power consumption data of deep-level mine compressed air systems.

In the third phase, the two novel developments are combined to compile a new simplified high-level investigation methodology. In the final phase of Chapter 3, the new single-variable input methods and tools are verified with existing multivariable approaches used in previous studies. This verification is conducted as follows:

- The novel benchmarking method is compared with a simulation and an available benchmarking method.
- The practical tool for quantifying potential energy savings is verified against complex simulation models and an existing multivariable simplified tool.

Chapter 4 – Validation

In this chapter, two actual compressed air systems of different South African deep-level mines are used as case studies. Quantifiable results are obtained by implementing the contributions of this study on the two case studies. These results are then used to validate the new contributions developed in this study.

Chapter 5 – Discussions and recommendations for further work

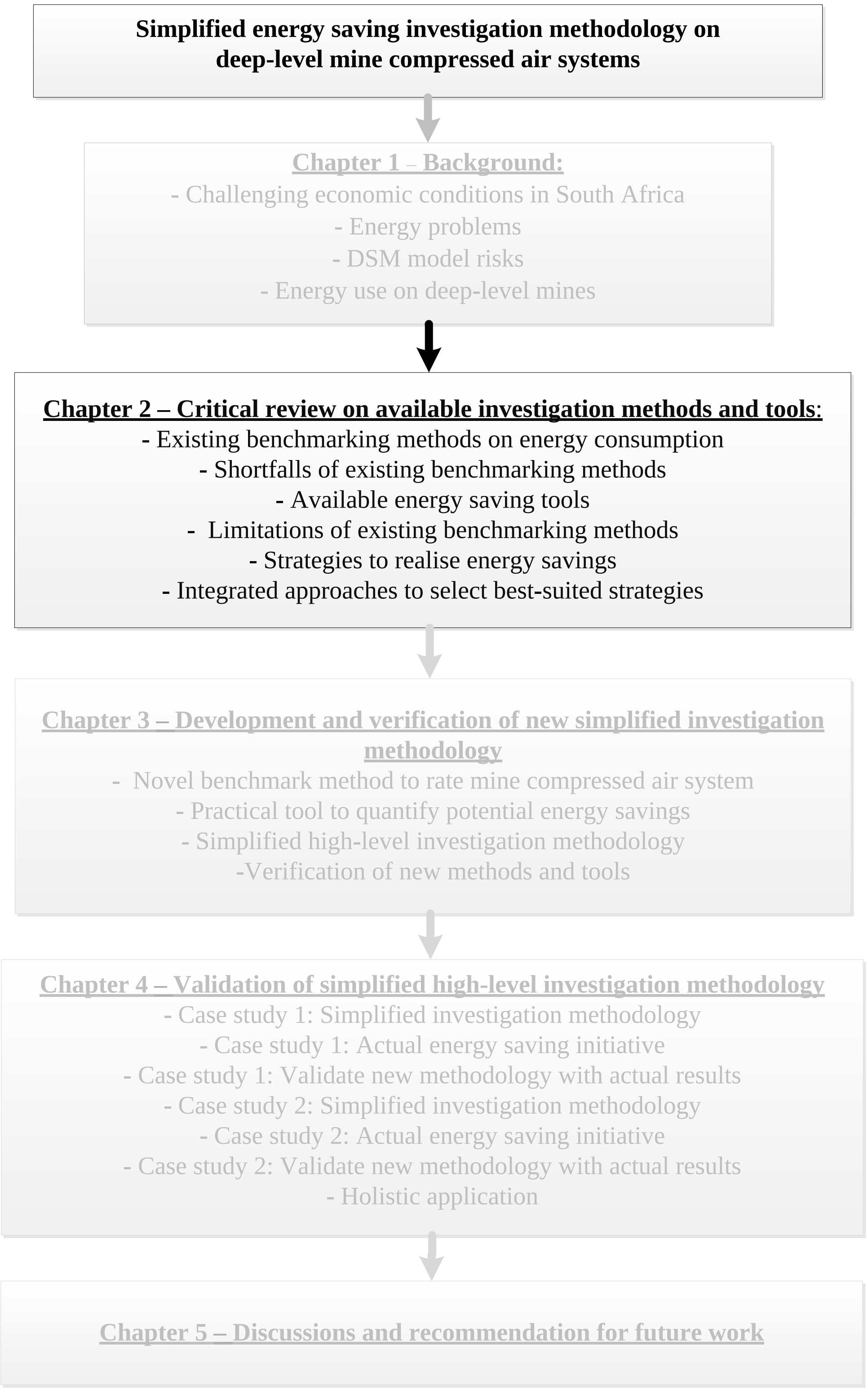
The final chapter discusses the study and provides recommendations for further work to reduce the electricity cost of marginal mines and potentially other energy-intensive industries further.

1.9 Conclusion

The background chapter conveyed information on current economic conditions and energy challenges that impact the sustainability of deep-level mines in South Africa. Due to mismanagement, compressed air systems have been identified by ESCOs as an area with significant potential for reducing power consumption. However, due to current financial constraints, marginal mines can no longer afford energy experts. ESCOs are thus required to risk the input when investigating new energy saving initiatives.

During investigations, extensive audits and simulations are needed to determine the viability and potential impact of the various energy saving initiatives. Current methods and tools used during investigations are costly and time-consuming, and they require skilled labour; therefore, they use significant ESCO resources. As a result, it is not feasible for ESCOs to investigate all projects. This highlights the need for ESCOs to investigate potential energy savings with minimal risks and input.

2 CRITICAL REVIEW ON EXISTING INVESTIGATION METHODS AND TOOLS



2.1 **Preamble**

Chapter 1 highlighted the contribution of energy initiatives towards a sustainable and growing mining environment in South Africa. Deep-level mine compressed air systems were identified as significant electricity consumers in this environment.

ESCOs are required to risk input and investment while investigating energy saving initiatives. In this chapter, a critical review is conducted to identify the shortfalls of the available investigation processes used while investigating new energy saving initiatives. These shortfalls were used to formulate the novel contributions discussed in Chapter 1. Current processes used during an investigation phase of energy saving initiatives include:

- Benchmarking to rank energy performances
- Saving identification tools to quantify potential savings

2.2 Existing benchmarking methods on energy consumption

2.2.1 Overview

This section focuses on previous studies and existing benchmarking methods used to rank energy performances. There are several studies that benchmark energy systems, but literature on benchmarking South African deep-level mine compressed air systems is limited. The objective of this section is to evaluate and consider existing benchmarking methods used in commercial and industrials sectors. Existing energy benchmarking methods on deep-level mine compressed air systems are then critically reviewed to determine the shortfalls and need for new benchmarking methods.

2.2.2 Available benchmarking methods used in commercial sectors

In 2012, Chan found that it is not practical to benchmark the overall energy use of hotels due to various factors that affect energy consumption. Chan divided a hotel’s total energy consumption into manageable sub-sections. These sub-sections each have a unique contribution to the total energy usage of the hotel [46].

This should be considered when benchmarking energy on deep-level mine compressed air networks. Applying Chan’s approach to industrial and mining applications simplifies complex systems. The study also highlighted the need to reduce the energy consumption of hotels and to create a best practice model.

In 2013, Keirstead completed a study in the United Kingdom on how to benchmark the energy usage of urban areas. Keirstead gathered data and determined the energy intensity per capita (kWh/capita). Various normalisation methods were applied due to significant inconsistencies in the data for energy intensity per capita. These normalisation methods included urban grouping classes, regression models for controlling external factors (climate), and defining specific energy efficiencies according to urban classes [47].

It was established that a simple method, such as grouping similar urban classes together, was sufficiently accurate when compared with complex statistical methods used to determine the efficiency of the different areas. With simplified methods such as grouping, fewer variables are required to determine the efficiencies and comparisons among different areas [47]. This will be considered when benchmarking mines.

In 2000, Filippín conducted a study in Argentina on energy benchmarking of schools. The purpose of the study was to benchmark the correlation between the energy demand and the number of students within a particular area [48]. The benchmarking method required both independent variables (power) and dependent variables (number of students in the area). Filippín considered ambient temperature, location of the schools, and the activities occurring in the schools as parameters. These external factors were not normalised and had a significant impact on the results. Thus, a benchmarking usage was not determined. Normalisation should be considered when benchmarking mines [48].

A benchmark study on energy consumed by air conditioning systems was conducted in Hong Kong by Mui et al. A statistical method was used to determine a correlation between the carbon dioxide concentration (dependent variable) and the energy (independent variable) required to cool air in offices. These variables proved to correlate well. The air temperature set point was also used as another dependent variable for investigating other correlations. Compared with the correlation between carbon dioxide and energy, it was found that the temperature set point correlated less with the energy consumed. The direct impact of different independent variables must be considered when benchmarking mines [49].

2.2.3 Energy benchmarking for industrial sectors

In many industries, energy is a major contributor to production cost. International competitiveness demands minimal production costs. Thus, more emphasis is placed on improving the energy efficiency of industries [50]. Benchmarking could be used to compare the performance of different industries and to identify potential savings [51].

In 2014, Ballantyne and Powell developed a benchmarking method that allowed mines to determine their comminution energy efficiency ranking. Ballantyne and Powell gathered production data from annual public reports of different mines. The most recent production data was also collected but was inconsistent with the reports. This led to inconsistencies in the results that followed. Power data was available from different sources, including AMM magazine and JKTech. Using a combination of these data sources, Ballantyne and Powell calculated the energy intensity per ounce (MWh/oz) of gold and copper produced [52], [53].

In 2012, Oda et al. compared the specific energy consumption of countries using fossil power generation within the steel and cement sectors. Figure 14 indicates the average fossil power generation for 27 countries from 2006 to 2008. These countries were sorted by energy efficiency [54]. The average fossil power generation efficiency was 37%. This average benchmarked method will be considered when benchmarking several different mines in South Africa.

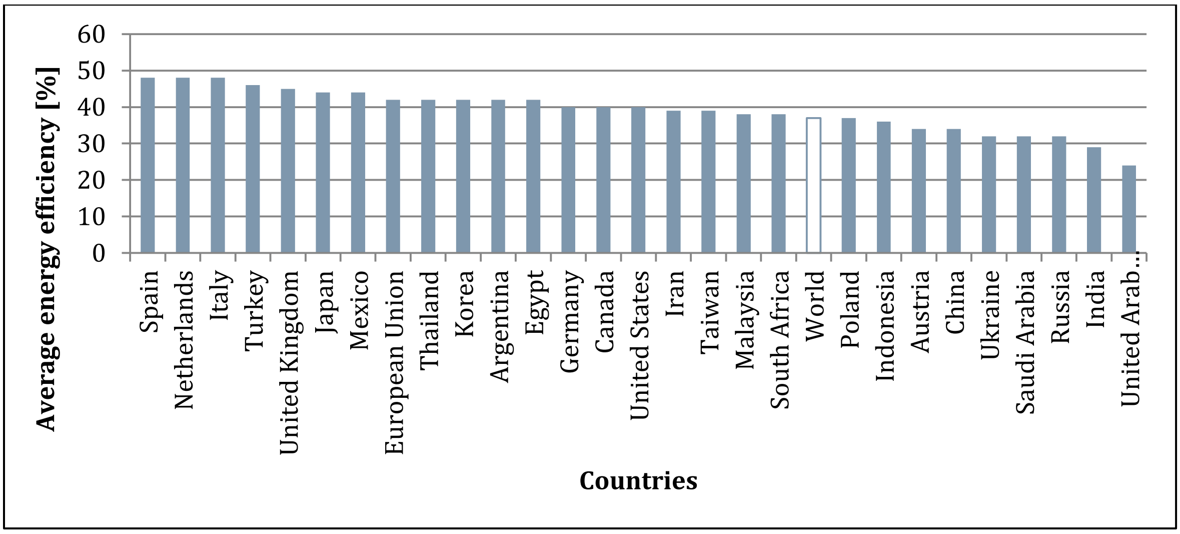


Figure 14: Average fossil power generation efficiency of 27 countries (adapted from [54])

In 2014, previous research by Chan et al. indicated that the iron and steel industry is one of the most challenging industries to estimate energy intensity due to the limitation of available data, system boundaries and calculation methods. However, potential energy savings of 28% could be achieved by implementing best practice technology [55].

In 2011, Saygin et al. researched the use of benchmarking as a tool to identify potential savings in developing countries. Due to the lack of data availability, benchmarking results have uncertainties. Quality and sufficient data is important for benchmarking and the results thereof. Saygin et al. collected information in curves that typically display the energy efficiency [56].

Figure 15 illustrates a plant's efficiency plotted as cumulative frequency curves in descending order. The curve starts with the most efficient plant and ends with the least efficient plant [56]. According to the study, best practice technology offers potential savings of 27±8% worldwide. Plotting curves and estimating potential savings compared with best practices will be considered when benchmarking mines.

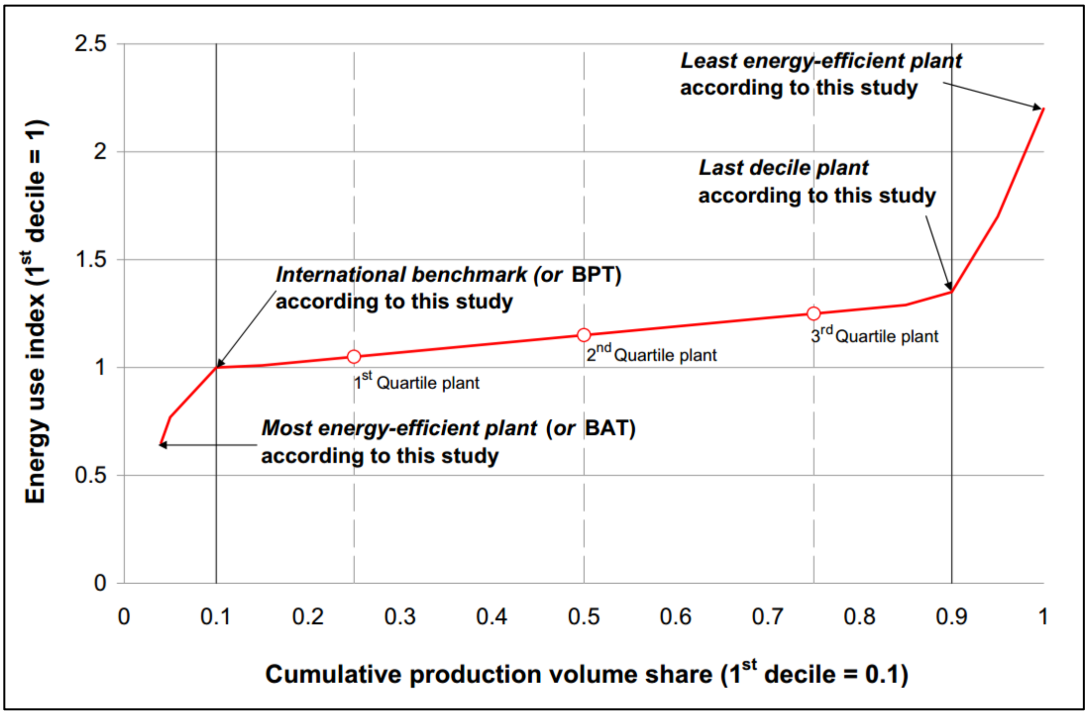


Figure 15: Energy benchmark curve for the manufacturing industry [56]

In 2013, Ke et al. found that industrial systems would never have the same processes and parameters where energy consumption is concerned. The study also found it difficult to obtain sensitive and accurate data. To realise the difficulties mentioned, Ke et al. recommended the following for process-based energy benchmarking, which will be considered when benchmarking mines [57]:

- Develop internal methods to benchmark systems without exposing sensitive data
- Acquire high-quality data
- Involve experienced and knowledgeable staff

2.2.4 *Benchmarking on deep-level mine compressed air systems*

Available benchmarking models for mining operations use a combination of dependent and independent variables as multivariable data sets [24], [33], [40]. These methods include electricity consumption, tonnes mined, mine depth and ambient conditions as summarised in Table 6. Although deep-level mines in South Africa have several high energy demand systems as indicated in Table 6, this study focuses on compressed air.

Table 6: Variables used in available benchmarking models on deep-level mines (adapted from [40])

HIGH-DEMAND SYSTEM	DEPENDENT VARIABLE	INDEPENDENT VARIABLES
Compressed air	Electricity consumption	Tonnes mined
		Mine depth
		Ambient conditions
Cooling	Electricity consumption	Tonnes mined
		Mine depth
		Ambient conditions
		Geographical location
Dewatering	Electricity consumption	Tonnes mined
		Mine depth
		Fissure water
Ventilation	Electricity consumption	Tonnes mined
		Mine depth
		Ambient conditions
		Geographical location
Hoisting	Electricity consumption	Tonnes mined
		Mine depth

Models using tonnes mined

Several studies have used either best practice or average benchmarking methods to identify mismanagement of electricity. Most of the available benchmarking methods determine the relationship between energy consumption and ore production. Previous benchmarking methods on deep-level mines mainly included production and energy consumption comparisons. This production data is typically available over long periods and is not readily available from all mines [40], [44], [58], [59].

A study by Barnard and Grobler found no correlation between production and energy use. However, the study only considered one mine’s monthly data correlations over a period of 18 months. The poor correlation found by Barnard and Grobler will be considered when benchmarking deep-level mine compressed air systems [35]. .

After several confidentiality agreements have been signed for the interest of this study and as part of a Section 12L income Tax Act, Mine A allowed access to their tonnes hoisted data. This highlights the challenge of data accessibility from mines. An evaluation was conducted on Mine A to evaluate the energy consumption correlation with production over a period of 12 months. Table 7 shows the tonnes hoisted (production) and energy consumed data for Mine A from January 2015 to December 2015.

Table 7: Production and energy consumed data from Mine A

MONTH	TONNES HOISTED	TOTAL ENERGY CONSUMED (KWH)
15-Jan	141 992	9 744 168
15-Feb	175 675	10 478 200
15-Mar	184 941	9 993 166
15-Apr	172 721	10 421 207
15-May	211 305	10 698 388
15-Jun	198 324	10 620 150
15-Jul	196 166	9 247 648
15-Aug	157 754	9 685 229
15-Sep	187 375	9 855 944
15-Oct	204 812	9 861 550
15-Nov	217 131	9 938 918
15-Dec	126 507	9 488 488
Total	**2 174 703**	**2 194 066**

In August 2015, Mine A had an incident. All shafts were closed due to an application of safety stoppages, which is known as Mine Health and Safety Act (MHSA) Section 54. According to the Chamber of Mines of South Africa, section 54 stoppages cost South African mines R4.8 billion in 2015 [60]. Although Mine A lost three weeks of operation, the tonnes hoisted during August were only 20% less than July, and 15% less than September. Therefore, its assumed that stockpiles are used as buffers for times when production is delayed.

Another two neighbouring mines were approached for their data, and the request was rejected. Data accessibility differs from mine to mine. There is a need for benchmarking methods that require less sensitive data variables than currently used with available benchmarking methods. After further discussions with mine personnel at Mine A, it was confirmed that stockpiles are used underground and on the surface to store ore as buffers when required. This will have an impact on regression models where energy consumption and production data are used as multivariable inputs.

A regression model was developed from data collected on Mine A to determine the correlation between tonnes hoisted and total energy consumed. Figure 16 illustrates the correlation during a summer period (September–May). The energy consumed was used as the dependent parameter and the tonnes hoisted as the independent parameter. The correlation during winter months was not determined due to the few data points that were available during winter months (June–August).

As seen from Figure 16, a poor correlation was determined with an R^2 value of 0.03. Barnard and Grobler followed the same approach with one mine's data for 18 months and determined an R^2 value of 0.01 [35]. Thus, the findings from the evaluation on Mine A corresponded with Barnard and Grobler's study.

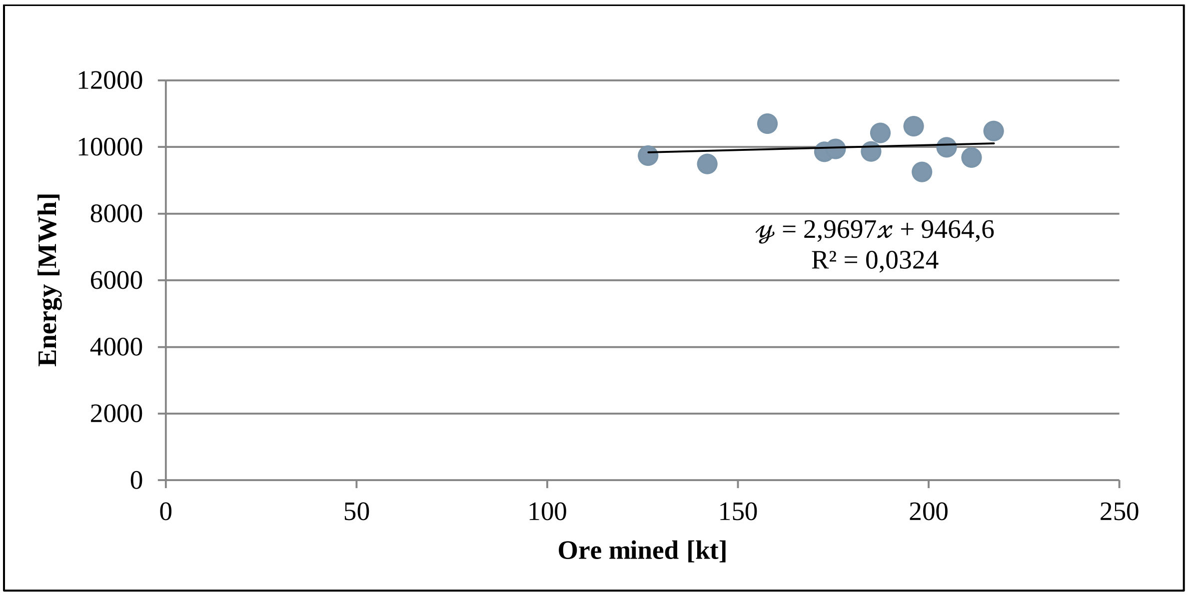


Figure 16: Compressed air energy consumption versus ore mined

Cilliers considered the monthly average data from various mines. One of Cilliers's data points represents one mine's monthly average energy intensity for a year (MWh/kt). He mentioned in his study that Barnard and Grobler disproved a correlation between compressed air energy and the amount of ore mined. However, Cilliers found a different outcome with an R^2 value of 0.65 during summer months and an R^2 value of 0.8 during winter months [40].

Van der Zee also conducted a benchmark study on compressed air energy use [33]. This benchmark approach, which is similar to Cilliers's method, required production and energy consumption data. The data is an average data set from various mines. One of his data points also represented one mine's monthly average energy intensity for a year. However, Van der Zee's data did not distinguish between winter and summer periods.

For further evaluation, Cilliers's regression method was implemented with Van der Zee's data set. As a result, an R^2 of 0.5 was achieved. This is significantly better than the study conducted by Barnard and Grobler ($R^2 = 0.01$) and the case study done on Mine A ($R^2 = 0.03$) [35].

Therefore, comparing the energy intensity of different mines (as done by Cilliers's) provide a better correlation than comparing the monthly energy intensity of one mine (see Figure 16). Thus, a need exists for a model that can be used with data points that represent a single mine's monthly average data points.

Models using mining depth and energy consumption

Cilliers obtained correlations of 87% and 83% between energy consumed and the mining depth during summer and winter respectively [40]. The deepest platinum mine in South Africa has an estimated depth of 1 750 m. Approximately 80% of the mines used in Cilliers study were deeper than 1 800 m.

Considering that typical platinum mines have depths of less than 1 000 m, it is assumed that platinum mines were not considered in Cilliers's study. From Chapter 1, it was found that platinum mines are the second-largest consumer in the mining sector. However, platinum mines should be considered in benchmarking models. Therefore, a need exists for a benchmarking method that considers mining at all depths.

Cilliers combined independent variables used for benchmarking deep-level mine compressed air systems to develop a multivariable regression model illustrated in Equation 1 [40]. The data used to develop this regression model was based on data sets of ten gold mines.

$$\boldsymbol{E_{comp} = 172.78 + 1.51(Z) + 33.36(T)} \tag{1}$$

With:

E_{comp} = Compressor energy requirement [MWh]

Z = Depth of mine [m]

T = Tonnes of ore mined [kt]

Van der Zee developed a simplified and cost-efficient benchmark approach for one company's gold mines [33]. He selected one company's gold mines (listed in Table 8) that had available production data. Platinum mines or other gold mines were not considered by Van der Zee. Thus, an assumption was made that both Cilliers and Van der Zee developed their benchmarking methods based on gold mines. This highlights the need for a benchmarking model that considers mines of all depths.

Table 8 shows the relevant data from the mines used in Van der Zee's study. It is indicated that Mine A and Mine E have the highest average monthly energy consumption. Therefore, Van der Zee focused on Mine A and Mine E for potential scope to reduce the potential energy savings.

Table 8: Energy consumption and tonnes milled data (adapted from [33])

MINE	COMPRESSED AIR CONTRIBUTION TO TOTAL ELECTRICITY USAGE [%]	AVERAGE MONTHLY TONNES MILLED [T]	AVERAGE MONTHLY ENERGY CONSUMPTION [KWH]	COMPRESSED AIR ENERGY USED PER TONNE MILLED [KWH/T]
A	36	72 638	7 481 692	103
B	13	35 404	4 956 509	140
C	28	45 034	6 439 840	143
D	41	33 838	2 673 181	79
E	15	91 878	8 544 619	93
F	22	32 304	4 102 668	127
G	8	67 31	2 154 00	32
H	20	111 661	5 136 425	46

Figure 17 shows that Mine E is deeper and has a lower energy intensity than Mine A. Thus, Van der Zee chose Mine A as the mine with scope for improvement. Van der Zee's approach requires three multivariable data sets to determine the mine with the most potential for scope for improvement. This should be considered when benchmarking compressed air systems on deep-level mines.

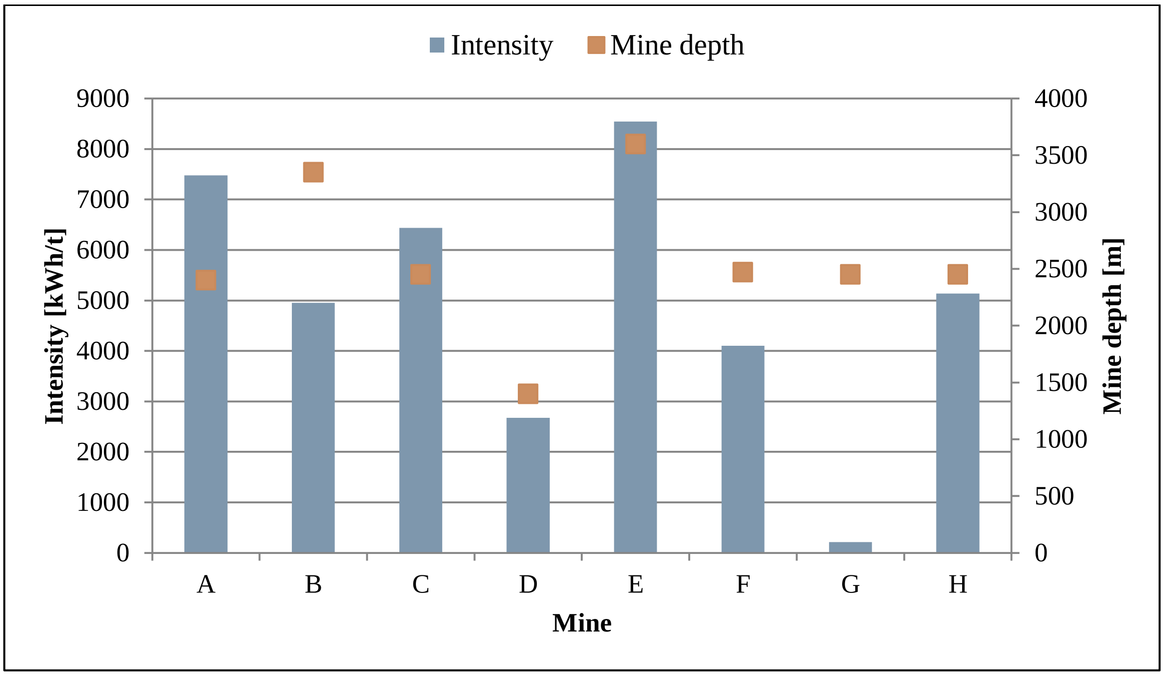


Figure 17: Mines used in Van der Zee's benchmarking method

Best practice benchmarking compares systems and operations with the best in class systems and operations. With the mines used in Van der Zee's data, Mine G (Figure 17) would be considered the best practice operation [33], [58].

The following steps are involved in best practice operations and management [58]:

- Identify the areas that will have most value to implement benchmark studies.
- Investigate the important indicators for measuring the performance of areas in need.
- Identify readily available data, and how to obtain the required data.
- Analyse data and compare best practice performances with the highest energy efficiency.
- Determine mitigation strategies for improving current operations and systems towards best practice performance.

Models using energy consumption as a single-variable benchmark approach

Energy data sources for mining are available in publications from several organisations including the Chamber of Mines and Eskom. The gold mines in Van der Zee's study were selected according to the availability of data. Van der Zee compared Eskom electricity use accounts with on-site power meters; these were found to be accurate within 2%. Thus, energy consumption can be obtained and verified by third parties. This should be considered when developing benchmarking models on deep-level mine compressed air systems.

Reliable and complete data sets are important for establishing benchmark values and progress measurements when comparing different mines [33], [58]. Verifying readily available data by a third party increases the data reliability significantly. This should be considered when benchmarking deep-level mine compressed air systems [21].

Tshisekedi implemented benchmarking on deep-level mines, which included both gold and platinum mines [58]. The main findings of Tshisekedi's study were compiled as an integrated benchmarking model of energy consumption data that can be used by mining personnel. This model created awareness on the energy consumption of different mining activities.

Tshisekedi considered total underground compressed air energy use in combination with the energy consumption of pumping, hoisting, loading, refrigeration and ventilation. The values could then be compared with the values from other mines. However, Tshisekedi did not benchmark profiles of compressed air systems as an individual activity [58]. This will be considered for benchmarking deep-level mine compressed air systems.

Another benchmarking method developed by Tshisekedi was based on a user-friendly Microsoft Excel™ model used by mines to illustrate the total annual energy consumption curves of the different mines. Figure 18 compares the annual energy consumption of four different mines. Figure 18 shows that Mine 4 has a significantly lower energy consumption profile than the other mines. Mine 1 can thus be assumed to be the most inefficient of the mines. These energy profiles enable mines to benchmark their energy consumption without considering production data. This will be considered when benchmarking deep-level mine compressed air energy use.

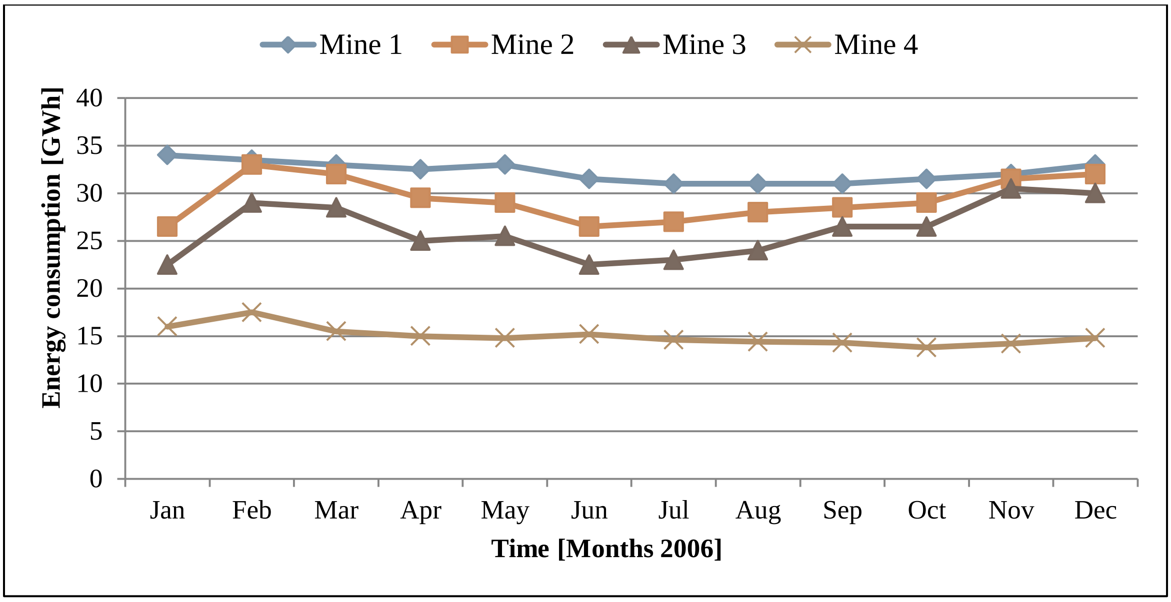


Figure 18: Annual energy consumption curves of different mines (adapted from [58])

Van der Zee identified the potential for compressed air optimisation if compressed air energy use profiles do not indicate mine production schedules [33]. Therefore, Van der Zee recommended that further investigations had to be done on energy use profiles of compressed air systems of different mines. This will be considered for benchmarking on deep-level mine compressed air systems.

2.3 Shortfalls of existing benchmarking

Section 2.2 highlighted the considerations from commercial and industrial industries that can be used when benchmarking deep-level mine industries. These considerations from the different studies are summarised in Table 9.

Table 9: Summary of previous work on commercial and industrial benchmarking

AUTHOR(S): DESCRIPTION AND REFERENCE	CONSIDERATIONS
Chan: Energy benchmarking in support of low carbon hotels: Developments, challenges, and approaches in China [46].	Chan divided total energy consumption into manageable sub-sections. These sub-sections each have a unique contribution to the total energy usage.
Keirstead: Benchmarking urban energy efficiency in the UK [47].	Grouping methods are sufficiently accurate when compared with complex statistical methods. Simplified methods require fewer variables to determine the efficiencies and comparisons among different areas.
Filippín: Benchmarking the energy efficiency and greenhouse gases emissions of school buildings in central Argentina [48].	Benchmarking was not established due to the complexity of determining the different impacts of numerous variables.

AUTHOR(S): DESCRIPTION AND REFERENCE	CONSIDERATIONS
Mui et al.: An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates [49].	The impact of different variables on specific operations must be considered when developing benchmarking models.
Phylipsen et al.: Benchmarking the energy efficiency of Dutch industry: An assessment of the expected effect on energy consumption and CO_2 emissions [51].	Benchmarking could be used to compare the performance of different industries and to identify potential savings. Industries find it challenging to estimate the energy intensity due to the limitation of available data.
Ballantyne and Powell: Benchmarking comminution energy consumption for the processing of copper and gold ores [53].	A benchmark method was developed that allowed mines to determine their comminution energy efficiency ranking. It was found that production data from annual public reports of different mines were inconsistent with current reporting data.
Oda et al.: International comparisons of energy efficiency in power, steel, and cement industries [54].	An average benchmarking method was used to compare iron and steel industries of 27 countries to a world average. It was found challenging to estimate the energy intensity due to the limitation of available data, system boundaries and complex calculation methods.
Chan et al.: Energy efficiency benchmarking of energy-intensive industries in Taiwan [55].	The iron and steel industry is one of the most challenging industries for estimating energy intensity due to the limitation of available data, system boundaries and calculation methods.
Saygin, et al.: Benchmarking the energy use of energy-intensive industries in industrialised and in developing countries [56].	Benchmarking was used as a tool for identifying potential savings in developing countries. Due to the lack of data availability, benchmarking results have uncertainties. Quality and sufficient data are important for benchmarking and the results thereof. Information was collected from curves that typically display the energy efficiency. Best practice technology data was compared with current energy usages to determine potential savings.
Ke et al.: Analysis and practices of energy benchmarking for industry from the perspective of systems engineering [57].	The study found it difficult to obtain sensitive and accurate data. Ke et al. recommended developing internal methods for benchmarking systems without exposing sensitive data.

The first contribution of this study was developed from the considerations, limitations and needs identified by available benchmarking methods on deep-level mine compressed air systems. These considerations, limitations and needs are summarised in Table 10.

Table 10: Summary of previous work on mine compressed air networks benchmarking

AUTHOR(S): DESCRIPTION AND REFERENCE	CONSIDERATIONS/LIMITATIONS	NEED FOR NEW METHODS/MODELS
Van der Zee: Modelling of electricity cost risks and opportunities in the gold mining industry [33].	1. Platinum mines were not considered in this study, only one company's gold mines. 2. Van der Zee recommended that further investigations be done on compressed air electricity profiles of mines. He identified that potential energy savings exist if the compressed air energy use profiles do not indicate production schedules. 3. Eskom accounts were used to verify mine power meters. The results were accurate within 2%. 4. Power consumption data of compressed air systems are available from most deep-level mines.	1. A need exists for a new benchmarking method that considers deep-level mines of all depths. 2. A benchmarking method is needed that requires minimal variables that are readily accessible. 3. The new benchmarking model should consider the power consumption profiling of compressed air systems.
Barnard and Grobler: Baseline service level adjustment methodologies for energy efficiency projects on compressed air systems in the mining industry [35].	The study used regression models with energy consumed and production data. No correlation was found between compressed air energy consumption and ore weight.	1. A benchmarking method is needed that requires minimal variables that are readily accessible. 2. A need exists for benchmarking methods that do not require production data.
Cilliers: Benchmarking the electricity use of deep-level mine compressors [40]. Benchmarking electricity use of deep-level mines [44].	1. Assumptions are made that platinum mines were not considered in developing the benchmarking model. 2. Multivariable data sets including production data are not always readily available. 3. Comparing the energy intensity of different mines provide a better correlation than comparing the monthly energy intensity of one mine (see Figure 16).	1. A need exists for benchmarking methods that do not require production data. 2. A need exists for a new benchmarking method that considers deep-level mines of all depths. 3. A benchmarking method is needed that requires minimal variables that are readily accessible. 4. A need exists for a regression model that can be used with data points that represent a single mine.

AUTHOR(S): DESCRIPTION AND REFERENCE	CONSIDERATIONS/LIMITATIONS	NEED FOR NEW METHODS/MODELS
Evaluation on Mine A.	1. The study used regression models with energy consumed and production data. 2. For baseline adjustments, no correlation was found between compressed air energy consumption and ore weight. 3. Stockpiles can affect regression models with production data as a dependent variable.	1. A benchmarking method is needed that requires minimal variables that are readily accessible. 2. A need exists for benchmarking methods that do not require production data.
Tshisekedi: Energy consumption standards and costs in the South African mining industry [58].	1. The combination of surface and underground compressed air end users was not considered in the benchmarking model. 2. Total energy use of compressed air systems of different mines was not compared. 3. Energy consumption data can be used as a single-variable to benchmark and compare mining operations.	1. A benchmarking model is needed that includes energy use of compressed air users on surface and underground. 2. A need exists for a benchmarking model that considers the total energy consumption data of compressed air systems.

2.4 Available energy saving identification tools

2.4.1 Overview

Benchmarking models are used to rank energy performances. Energy systems performing below average benchmarked systems have more scope for potential energy savings. Energy saving identification tools can be used as a next step to quantify these potential energy savings.

This section focuses on previous studies of existing saving identification tools used to quantify potential energy savings. Several studies of energy saving identification tools are available, but the literature on saving identification tools used on deep-level mine compressed air systems is limited.

The objective of this section is evaluating and considering existing saving identification tools used in commercial and industrial sectors. Existing saving identification tools used on deep-level mine compressed air systems are then critically reviewed to determine the shortfalls and need for new tools for quantifying potential savings.

2.4.2 Existing tools used in commercial operations

The rehabilitation of cities, residential- and commercial buildings are being encouraged. However, it is well-known how difficult it is to determine the energy savings achieved by implementing energy saving strategies. Detailed simulation tools are used to address these challenges. Existing buildings have a significant potential for energy savings. Thus, emphasis should be placed on rating building renovations [61].

Assumptions are made when using simulation tools with poor data quality. In 2016, Félix et al. found that energy saving estimations used with simulation tools often differ from actual measured data. A publication of Félix et al. aimed to accommodate this deviation between simulation and real results by using accurate measured data for a simulation tool instead of estimations. This provided a solution for generating baselines for saving verification and energy management. This will be considered when using energy saving identification tools on deep-level mine compressed air networks [61].

The energy performance of buildings must be assessed before any improvements are made. This will identify the potential scope for improvement on the buildings. Apart from scope identification, the building can also be categorised among other buildings. Typical uniform and approved tools used to classify buildings are energy rating, energy labelling, energy certification and energy benchmarking (as seen in Section 2.2) [62].

The energy use performance of existing buildings can be evaluated by using either the building as a whole, or using multilevels within a building. When using benchmarking methods, it has been found to be more effective to evaluate the energy performance of a building as a whole than to evaluate on a multilevel. The advantage of a multilevel evaluation is that more specific problem areas can be identified and improved for energy saving measures. This will be considered when using energy saving identification tools on deep-level mine compressed air systems [63].

Three approaches typically used for quantifying energy use of buildings include a calculation-based approach with simulations, a measurement-based approach with sub-metering, and a hybrid approach, which is a combination of calculation and metering. Energy use accounts are readily available and reliable, which makes it easier to analyse the energy use performance of buildings as a whole. These accounts are found to be inefficient for multilevel assessments [63]. This will be considered when implementing energy saving identification tools on deep-level mine compressed air systems.

In 2017, Peyramale and Wetzel presented an energy savings approach that classified the energy saving potential of different buildings. A uniform scoring method developed in the study followed a holistic approach to prioritise buildings and the specific areas in need of improvement [64]. With this method, real estate portfolios can be classified according to potential energy saving.

One of the study's aims was minimising the cost and effort input during the investigation phase. This was achieved by implementing a fast visual inspection to identify areas with significant scope for improvement. Colour was used as an additional visual representation. Green represented a high savings potential; red indicated a low saving potential. This will be considered as a cost- and time-efficient approach when implementing energy saving identification tools on deep-level mine compressed air systems [64].

The objective of this scoring method is to rank all relevant elements of each property either in a graphical or tabular arrangement. The potential for improvement was ranked according to an overall average grade. This ranking list provided a platform from which properties could easily and efficiently be evaluated to identify where to invest in energy efficiency improvements. It also identified properties with the optimal ratio between effort and measures to be taken. This will be considered when using saving identification tools on deep-level mine compressed air systems.

In 2015, Murray et al. conducted a study to understand usage patterns of electric kettles and their energy saving potential. It was found that kettle usage has increased and that 97% of households in the United Kingdom owned a kettle [65], [66]. A modern electric kettle has a self-contained heating unit. The heating unit heats water till the water reaches either boiling point or a present temperature. This type of kettle differs from traditional stove kettles that are less energy-efficient [67].

A need existed to investigate customer behaviour regarding kettle usage due to an absence of energy efficiency labelling guidelines, the availability of technology at that time, and consumers' mindsets and behaviours. Murray et al. assessed kettle usage and quantified the predicted energy consumed by households. The study proposed a tool for determining energy waste based only on load measurements [67].

The proposed tool also predicted potential energy savings if behaviours changed to filling kettles according to the most efficient water levels. Although the proposed tool determined energy waste by only using load measurements, the water consumption had to be quantified to determine the power wastage.

Thus, this approach could be considered as a multivariable approach. In summary, Murray et al. used load management as a tool for identifying potential savings if the inefficient behaviour of kettles was optimised. They also created awareness by enabling customers to see the impact of best practice technologies. This will be considered when developing tools to quantify potential savings within compressed air systems.

2.4.3 Identifying energy savings in industrial operations

Compressed air is mainly used in the service and industrial sectors due to the simplicity and safety of its production and handling. However, similar to the mining sector, compressed air is energy intensive and contributes significantly to the total energy use of the industrial and service sectors [68]. Thus, energy managers target compressed air energy use to reduce operational cost and increase profitability [68].

In 2009, Saidur et al. identified auditing as an effective tool for describing and pursuing energy management. The study focused on energy management by auditing energy consumed by electric motors. Saidur et al. considered the following as objectives of a compressed air energy audit [68]:

- Identify the energy use of compressed air in the industry.
- Identify energy wastages of compressed air.
- Implement energy savings measures to reduce inefficient usage.
- Provide a benchmarked energy usage of compressed air in other industries.

Energy management through an auditing process requires a competent team to identify, achieve and maintain energy savings. This team is typically a skilled consulting team, who is labour- and cost-intensive [68], [69]. This will be considered when using saving identification tools on deep-level mine compressed systems. A typical auditing process is illustrated in Figure 19.

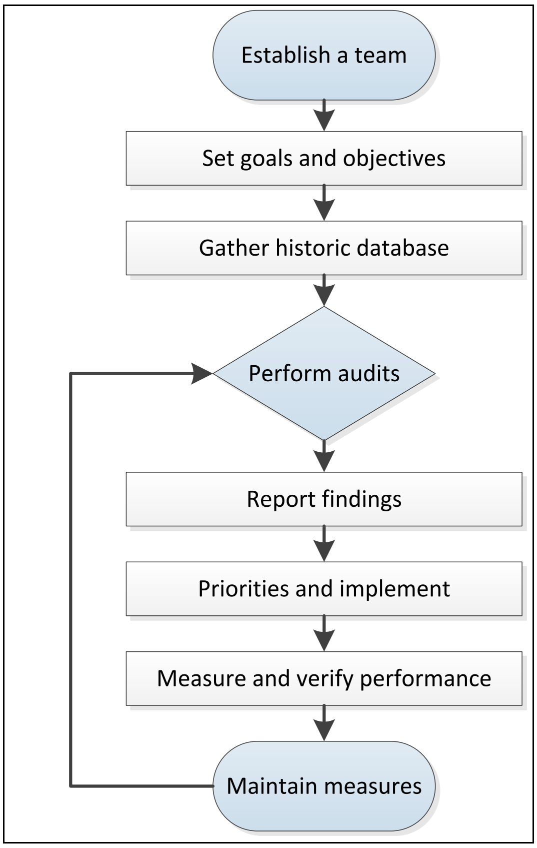


Figure 19: Typical energy audit process, adapted from [68]

The study by Saidur et al. found that historical data can be time-consuming and challenging to collect due to limited availability and accessibility. Saidur et al. identified important multivariable data sets needed for a compressed air energy analysis. These multivariable data sets include power, production, billing, TOU, mass flow rate, pressure and temperature data. These variables can be used to mathematically calculate or simulate potential energy savings [68], [69]. However, it must be considered that simulation software is costly, requires skilled workers (hard to use) and depends on several data variables to estimate potential savings accurately [16].

Two approaches previously used to identify energy saving potential are a single-site approach, which optimises the energy consumption of one specific site, or an area-wide approach, which views multiple sites as one entity [70], [71]. In 2015, Matsuda conducted an area-wide approach on one of the largest heavy chemical complexes. Matsuda used an R-curve analysis for an area-wide approach to evaluate the existing energy efficiency and the potential for optimisation [70].

The analyses were also further implemented on a second complex. By implementing the R-curve analysis on another complex, two complexes could be compared. Chiba was found to be more efficient than the Mizushima complex. Thus, Mizushima had more scope potential for efficiency improvement. The R-curve analyses were further implemented on individual sites within the different blocks in the Mizushima complex.

The R-curve analysis could be considered as a tool for assessing the energy efficiency performance of individual sites, different blocks and complexes as a whole. The tool can also be used for quantifying scope for potential energy savings. Thus, curves (profiles) can be used as energy saving identification tools. This will be considered when using energy saving identification tools on deep-level mine compressed air systems.

2.4.4 Energy saving identification tools for deep-level mine compressed air systems

Deep-level mines in South Africa have multiple compressors that interconnect with vast pipe networks on surface and underground. Compressed air is one of the largest energy consumers on South African mines, and is known to waste energy through either inefficient control or unwanted demand such as leaks [17]. Thus, these networks have significant potential for energy savings. However, the size, age and complexity of these networks make it very challenging to obtain the required parameters to simulate compressed air systems accurately [16].

Simulating complex compressed air systems is time-consuming and labour-intensive. Not all mines currently have the resources or personnel available to implement simulations with software. Previous studies found that simulations can take several weeks [12], [72]. A need exists for simplified methods to quantify potential energy savings on complex mine operations.

A trial-and-error approach is an alternative to simulations. However, considering the complexity of mine operations, a trial-and-error approach could lead to a combined resource cost of 1 700 hours to identify potential opportunities for energy optimisation. Limited accessibility to necessary data contributes to the prolonged investigation periods [12], [72]. A need exists for a simplified model that requires only readily accessible data from most mines to quantify potential energy savings.

Should available data sets be insufficient, detailed investigations and audits are necessary to collect all required data and information needed to simulate and quantify potential energy savings. These project investigations do not guarantee the potential savings quantified. Thus, all investments could be lost if these investigations do not realise the potential savings [17]. Due to the typical challenges experienced, some studies found it unfeasible to use complex calculations and software as tools for identifying potential savings. Previous research indicated that financial and operational risks exist when implementing costly initiatives without proper evaluation studies. Therefore, a need exists for a practical approach to evaluate potential energy savings without extensive resources [73].

Previous work indicated that potential savings could not be estimated accurately, and are commonly overestimated [74]. Available simulation tools require data from compressed air systems that are not readily accessible from most mines. Poor measuring techniques and insufficient instruments contribute to challenges regarding readily accessible data.

When data is inadequate, the data of relevant parameters is typically estimated. These parameters include pipe length, elevation, flow rate, pressure and pipe roughness [17], [75]. However, poor estimations result in inaccurate calculations. Previous work on compressed air networks found that simulated and actual data can differ by as much as 27% [17], [75]. A need exists for quantifying potential energy savings with sufficient accuracy and minimal input data.

In 2012, Marais developed a simplified approach in his study to quantify potential energy savings. This approach reduced both labour intensity and time spent to quantify potential savings. The approach focused on the relationship between power consumption and system pressure. Figure 20 illustrates the impact of reduced system pressures considering both constant compressor discharge pressure and reduced discharge pressures. Both scenarios were simulated with a fixed leak size at different pressures. A constant discharge pressure ranging from 700 kPa to 300 kPa was assumed for this simulation [17].

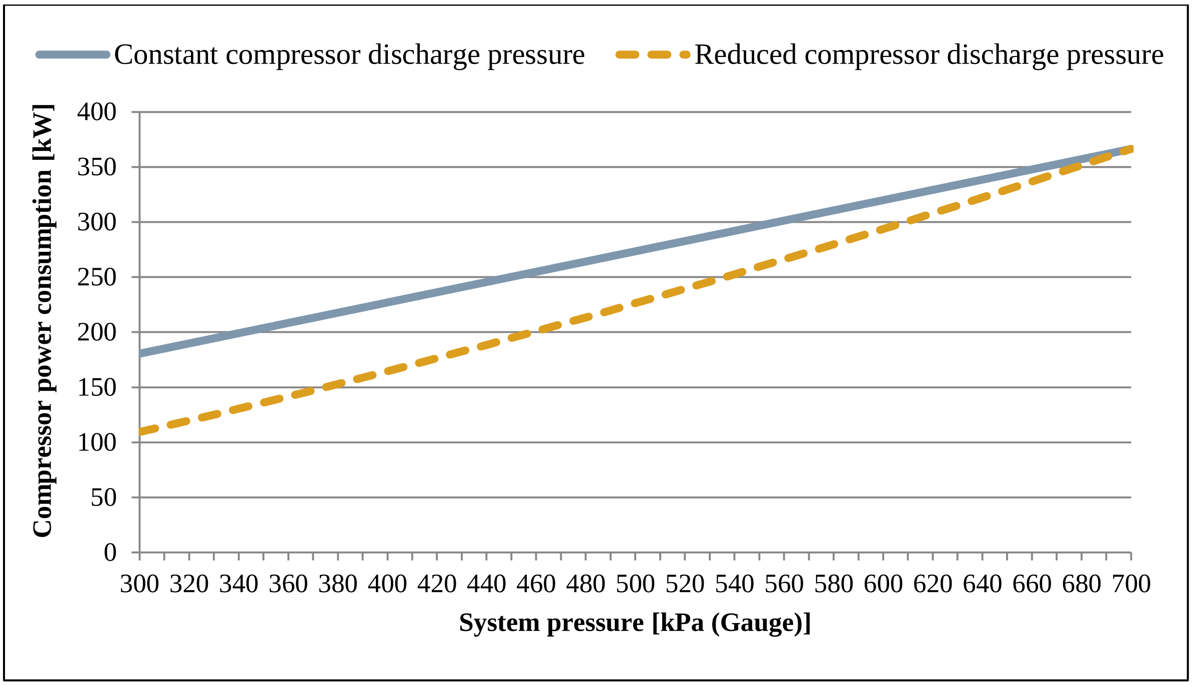


Figure 20: Impact of the reduced system on compressor power consumption [17]

By evaluating the results in Figure 20, a factor ranging from 1.6 to 1.8 can be used to estimate the compressor power saving because of reduced compressor discharge pressure. Thus, an absolute pressure reduction of 10% should result in a theoretical energy saving between 16% and 18% [17].

A method (general rule of thumb) previously used to calculate potential savings due to a reduction in system pressure states that a 1% power saving will be achieved for every 14 kPa pressure decrease in the system pressure [17], [76], [77]. This energy reduction is equal to a factor of 2, which is higher than the range calculated by Marais. An assumption is made that the factor is greater due to the impact of line friction, which Marais's method has not considered [17].

Marais's method can be regarded as a more conservative method for quantifying potential savings. This method was validated with an energy saving project that was implemented on a deep-level mine, which will be referred to as Mine B. The existing control on Mine B was automated before implementing an energy saving project. However, the existing control led to a frequent stop-start sequence of compressors during non-drilling shifts. The existing system pressure baseline of Mine B is shown in Figure 21 [17], [59], [78].

Figure 21 clearly shows that the system pressure is the lowest during the drilling shift (07:00–14:00). Typical mining operations require the highest system pressure during drilling shifts because extra compressors operate during this shift. Thus, the pressure profile and power profile should correlate and indicate the different shifts [17]. Van der Zee indicated that more research was required regarding the correlation between power consumption and mining operations [33].

A new energy saving project was implemented to optimise the existing automated stop-start compressor control of Mine B. With the new control, one compressor alternated between load and off-load positions, while another shifted between the maximum and minimum guide vane angles. As a result, the frequent stop-start sequence was opposed. This led to reduced system pressures that enabled an average daily power saving of 1.07 MW [17], [78].

After implementing the new compressor control, it was found that the compressors still consumed energy when operating in off-load conditions and at reduced guide vane positions. Thus, control parameters were further optimised, which increased the average daily power saving impact to 2.4 MW [17] [79], [80]. Due to the additional optimisation, only two compressors were required during non-drilling shifts. Thus, one fewer compressor was operated than with the existing operation before optimisation. Figure 21 compares the baseline system pressure profiles (operation before optimisation) with the system pressure profile after further optimisation [17], [79].

Analysis of Figure 21 indicates that the system pressure has reduced significantly during non-drilling shifts and has increased during drilling shifts. As a result, the system pressure reduced by 18% while the power consumption reduced by 29%. Considering Marais's simplified method, the ratio between the system pressure and power consumption reduction is 1.6. This supports Marais's method that estimates a ratio between 1.6 and 1.8 [17]. Thus, ratios of power consumption during different mining shifts will be considered when quantifying energy saving potential on deep-level mine compressed air systems.

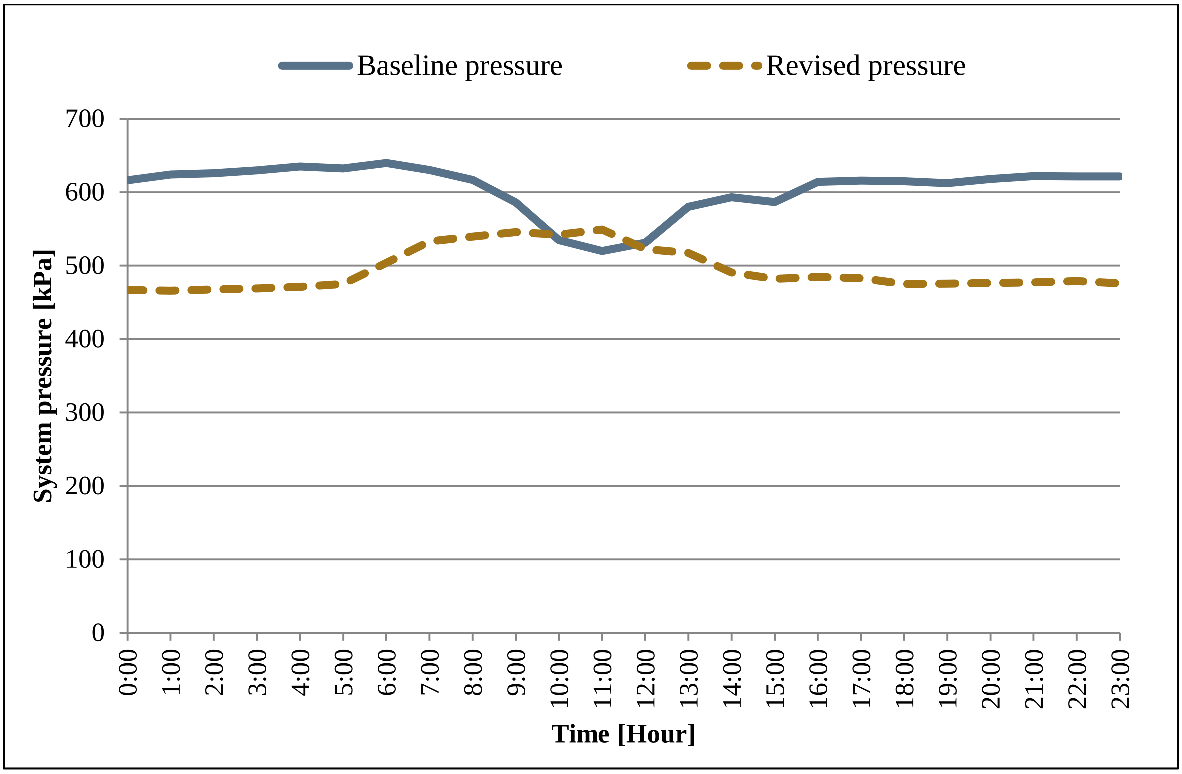


Figure 21: System pressure profiles prior and after optimisation [17], [79]

In 2014, Van der Zee identified the need for further work regarding the power consumption profile of compressed air. He identified that potential for savings exists if compressed air energy use does not indicate the production schedules. This corresponds with the findings of the energy saving project implemented on Mine B and will be considered when using energy saving identification tools on deep-level mine compressed air networks [33]. Several other energy saving projects were used to test Marais's approach. Some of these results ranged between a ratio 1.4 and 1.6, which is lower than the expected theoretical range of 1.6 and 1.8

Marais stated inconsistent data sets made it challenging to assess the impact of reduced system pressure on the power consumption. Marais simplified approach is, however, a theoretical expected range and can be used as a conservative method for estimating potential energy savings on compressed air networks [17]. This simplified tool is only applicable if the pressures remain between 300 kPa and 700 kPa [17]. Thus, a need exists for a simplified savings quantification tool that does not require multivariable data sets that include pressure. This will be considered when developing energy saving identification tools on deep-level mine compressed air systems.

Kriel implemented a DSM project underground on deep-level mines. Kriel identified areas for improvement and quantified the potential savings through simulations. Key parameters such as flow and pressures had to be measured underground to investigate potential savings. This specific mine already had underground valves with pressure and flow meters installed. The challenge was that most of these valves and measuring instruments were not in working condition and had to be repaired first. This prolongs data acquisition during investigation periods [81].

The study found that flow and pressure data of each level was crucial for identifying areas for potential improvement. This data was also relevant to Kriel when he quantified the potential energy savings on the compressed air system as a whole. Due to the insufficient number of measuring instruments in working order, the required measurements had to be taken manually with portable flow meters. The next step was to determine whether existing controls were functional. These interventions contribute to extended investigation periods [81].

The objective of the existing control was to lower the supply pressure of specific levels during the day. It was found that the supply pressure set point from the valves did not correspond with the actual pressures. The existing control requested a lower supply pressure during Eskom's evening peak periods. Figure 22 illustrates an example of the pressures on a level. This was the case for all levels except one. As a result, it was identified that the existing underground valve control did not operate according to design [81].

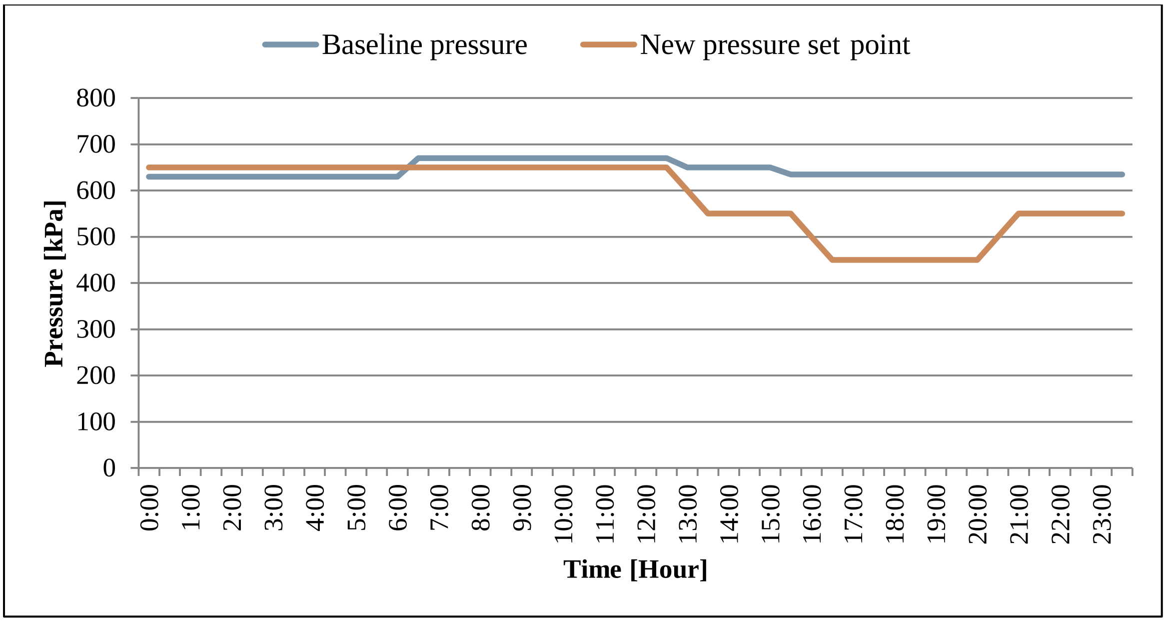


Figure 22: Baseline pressure demand compared with new required set point pressure

After repairing the valves, measuring instruments and existing control according to design specification, the next step was simulating potential impact of improved underground air distribution control. To determine the feasibility of a proposed energy saving initiative, the potential energy saving had to be quantified. A simulation model was used to quantify the potential savings. The following steps were used to develop a simulation model [81]:

1. Identify, formulate and understand the problem.
2. Determine data sets required.
3. Collect required data sets.
4. Formulate simulation model.
5. Perform simulation and understand results.

Step 1:

The initial step is to conduct fault-finding of existing equipment along with the existing strategy functionalities. Additionally, the schedules of different levels must be evaluated [81]. This step is, however, time-consuming and labour-intensive. ESCOs will risk time and input during this phase [12], [17], [74], [75].

Step 2:

To determine the required data sets, the equations used in the simulation must be understood [81]. These simulations are relatively complex and are typically studied by skilled workers [12], [17], [74], [75].

Step 3:

For this step, the necessary data required for the simulation model has to be collected. This specific model requires pressure and flow on the surface and each level, and the total power consumption of all compressors [81]. The required data is not always readily accessible or available. This step could thus prolong investigation periods [12], [17], [74], [75].

Step 4:

The fourth step requires formulating the simulation model. Formulating can commence if Step 1 and Step 2 have been completed successfully. Kriel provided a procedure to follow when formulating the simulation model. This procedure is shown in Figure 23. ESCOs as energy experts risk input during investigation periods when formulating simulation models [12], [17], [74], [75], [81].

Step 5:

The final step is performing the simulation model develop from Step 1 to Step 4. If the values are not accurate, the prediction can be significantly different to the actual impacts [12], [17], [74], [75], [81].

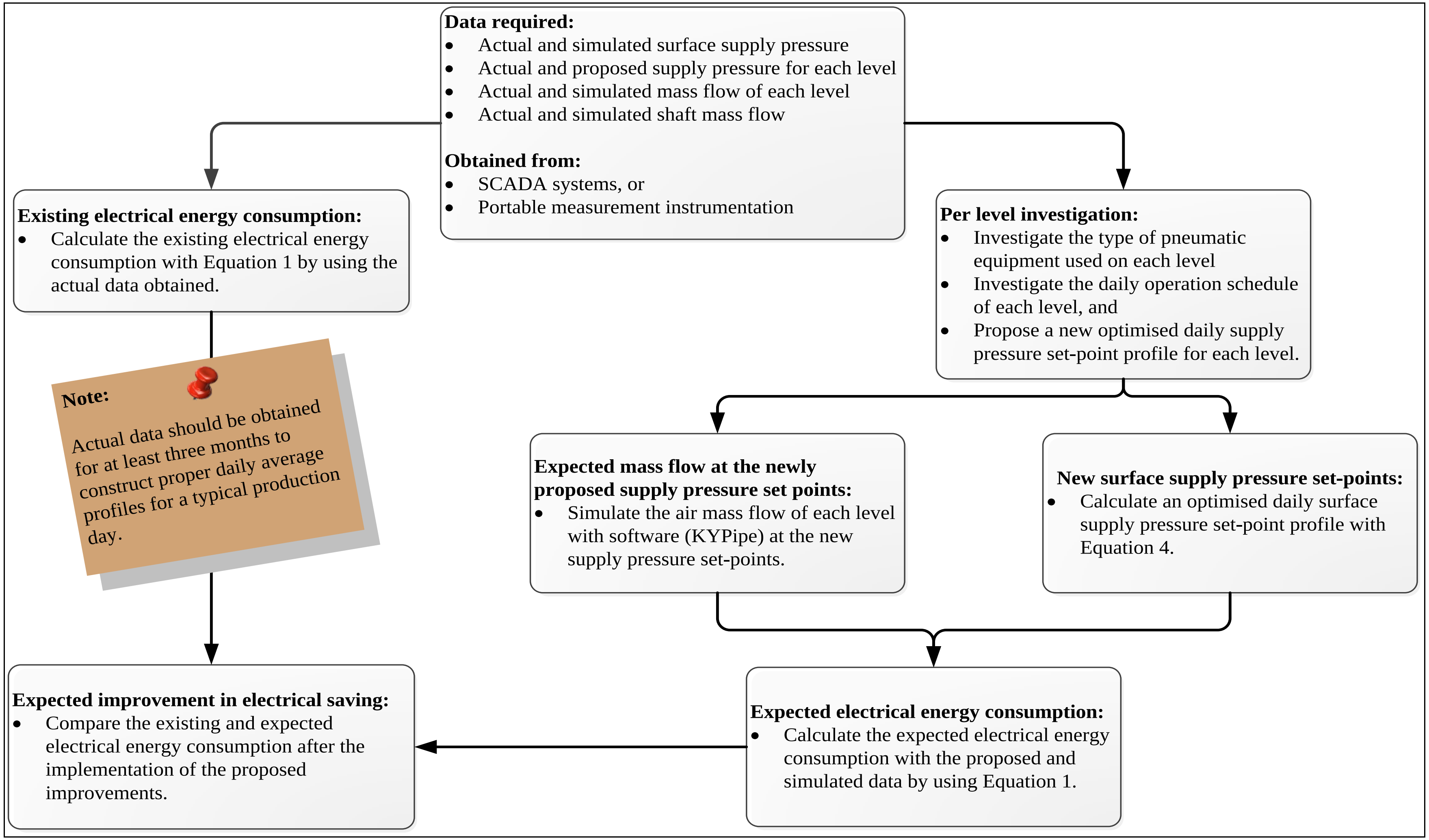


Figure 23: A procedure followed to quantify potential energy savings with simulations (adapted from [81])

2.5 Limitations of existing tools

Several studies on energy saving identification tools have been investigated in this section. Section 2.4 highlighted considerations from commercial and industrial industries that can be used when implementing energy saving tools in deep-level mine industries. These considerations are summarised in Table 11.

Table 11: Summary of available commercial and industrial energy saving identification tools

AUTHOR(S): DESCRIPTION [REFERENCE]	CONSIDERATIONS
Maré et al.: Novel simulations for energy management of mine cooling systems [12].	1. Simulations require multivariable data sets. 2. Simulation packages are complex, labour-intensive and time-consuming. 3. A need exists for simplified methods to quantify potential savings on complex systems.
Félix et al.: ME3A: A software tool for the identification of energy saving measures in existing buildings: Automated identification of saving measures for buildings using measured energy consumption [61].	1. Félix et al. found that estimations from simulation tools differ from actual measured data due to assumptions that were made. 2. This study uses a simulation tool with actual measured data instead of estimations. 3. The tool provides a solution to generate baselines for savings verification and energy management.
Yan et al.: A simplified energy performance assessment method for existing buildings based on energy bill disaggregation [63].	1. Evaluating energy performance of a whole building with benchmark references is effective and simplified compared with multilevel evaluation. 2. Energy use accounts are readily available and reliable, which makes it easier to analyse energy use performance of buildings as a whole.
Peyramalea and Wetzel: Analysing the energy saving potential of buildings for sustainable refurbishment [64].	1. A uniform scoring method developed in the study follows a holistic approach to classify and prioritise buildings, and determine specific areas with the most need for improvement. 2. A ranking list provides a platform from where properties can be evaluated to identify low-risk opportunities for investment. It also identifies properties with the optimal ratio between effort and measures to be taken. 3. The study aimed to minimise the cost and effort input during the investigation phase. This was achieved by implementing a fast visual inspection with colours such as red and green to identify areas with more and less scope for improvement.
Murray et al.: Understanding usage patterns of electric kettle and energy saving potential [67].	1. The study proposed a tool for determining energy waste based only on load measurements. 2. The tool identifies potential savings and also creates awareness by enabling customers to see the impact of best practice technologies.

AUTHOR(S): DESCRIPTION [REFERENCE]	CONSIDERATIONS
Saidur et al.: A review of compressed air energy use and energy savings [68].	Energy management through an auditing process requires a competent team to identify, achieve and maintain energy savings. This team is typically a skilled consulting team, and is labour- and cost-intensive.
Matsuda et al.: Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve the performance of highly efficient process plants [70].	1. An R-curve analysis was used as a tool for assessing the energy efficiency performance of induvial sites, different blocks and complexes as a whole. 2. The tool can be used to identify scope for potential energy savings. Thus, curves (profiles) can be used as energy saving identification tools.

The second contribution of this study was developed from the considerations, limitations and needs identified within available energy saving identification tools summarised in Table 12.

Table 12: Available energy saving tools of used on deep-level mine compressed air systems

AUTHOR(S): DESCRIPTION [REFERENCE]	CONSIDERATIONS/LIMITATIONS	NEED FOR NEW METHODS/MODELS
Marais: An integrated approach to optimising energy consumption of mine compressed air systems [17].	1. Van der Zee identified that potential energy savings exist if compressed air energy use does not indicate the production schedules. This corresponds with the findings in Marais's study on the energy saving project implemented on Mine B. 2. Marais stated that inconsistencies of data sets made it challenging to assess the impact of reduced system pressure on the power consumption. 3. Marais's simplified approach can be used as a conservative method for estimating potential energy savings on compressed air networks. This tool is only applicable if the pressures remain between 300 kPa and 700 kPa. 4. Simulating complex compressed air systems are time-consuming and labour-intensive.	1. A need exists to evaluate the use of compressor power profiles as a method to identify potential savings. 2. A simplified tool is needed that do not require multivariable data sets that include pressures and flows. 3. A simplified, cost-effective method is needed to quantify potential savings with minimal labour intensity.
Kriel: Modernising underground compressed air DSM projects to reduce operating costs [81].	1. Multivariable data sets are required to formulate the simulation model. 2. Time-consuming fault-finding investigations are required to repair faulty equipment. 3. Portable measurements were required to obtain required data sets. 4. The simulation procedure as a whole could be time-consuming and requires skilled workers.	1. A practical identification tool is needed that can be used in short time periods. 2. A simplified tool is needed that does not require multivariable data sets including pressures and flows. 3. A need exists to quantify potential savings with minimal labour intensity.

AUTHOR(S): DESCRIPTION [REFERENCE]	CONSIDERATIONS/LIMITATIONS	NEED FOR NEW METHODS/MODELS
Mare et al.: Evaluating compressed air operational improvements on deep-level mine compressed air systems [73].	Financial and operational risks exist when implementing costly initiatives without proper evaluation studies	A need exists for a practical approach to evaluate potential energy savings without extensive resources
Snyman: Integrating various energy saving initiatives on compressed air systems of typical South African gold mines [74].	Potential savings could not be accurately estimated due to poor data quality. Therefore, potential energy savings are usually overestimated.	An energy saving identification tool is required that can quantify potential savings with sufficient accuracy and limited data as input.
Scheepers: Implementing energy efficiency measures on the compressed air network of old South African mines [75].	1. Commercial simulation tools require data from compressed air systems that are not readily available or accessible from all mines due to insufficient instrumentation and measurement techniques. 2. Poor estimations result in inaccurate calculations. Simulated and actual data can differ as much as 27%.	1. An energy saving identification tool is needed that use readily available and verifiable data. 2. A sufficient accuracy saving identification tool is required.

2.6 Strategies to realise energy savings

2.6.1 Overview

Numerous strategies have previously been implemented on deep-level mine compressed air systems. Most of these strategies either reduced the total daily electricity consumption (energy efficiency) or the electricity during evening high-demand periods (load clipping). Most of these strategies were implemented through IDM-funded initiatives previously discussed in Chapter 1.

Previous research found that implementation of new energy saving initiatives necessitates time-consuming and resource-intensive investigations. Energy efficiency typically requires more input to realise savings throughout the production day whereas as load clipping projects only focus on savings within the Eskom evening peak period. Energy efficiency projects would add more value to the client; however, considering that current IDM models only reward load reduction within Eskom's peak period, ESCOs focus mainly on load clipping projects. By being aware of the project types required to improve the energy use of systems, ESCOs and mines can invest the necessary risk and input more efficiently [40], [44].

Simulations and audits are used to identify either energy efficiency or load clipping projects to achieve potential energy savings. These projects involve strategies that optimise either the demand or the supply side. Compressor control and selection systems can be used to optimise the supply side, whereas surface and underground air distribution can be optimised to control the demand side. This chapter discusses the background on existing strategies used to achieve potential savings, and evaluate available methods used to determine best-suited strategies to realise energy savings.

2.6.2 Compressed air supply optimisation

The compressed air supply can be optimised through improved control systems. This section discusses existing strategies used to optimise compressed air supply through typical control systems. The airflow rate into a centrifugal compressor can be controlled by restricting the airflow with guide vane angles or inlet butterfly valves.A reduced flow rate results in decreased power consumption. The challenge is to maintain the minimum required flow to prevent surge. Surge occurs in a compressor when the flow direction is reversed. As a result, damaging flow fluctuations occur within the compressor. The negative impacts of surges include excessive vibrations, thrust on the driveshafts, and reheating of reversed flow [17], [78], [82], [83].

Compressor control systems can be used to ensure that compressors operate at the most efficient points. The delivery pressures and valve positions of a compressor are determined with set points. A PLC usually controls these set points. Inefficient control and incorrect set point operations could result in unnecessary power consumption [17].

Power consumption during an unloaded condition depends on the compressor’s specific characteristics. During unloaded conditions, the power consumption could typically vary between 20% and 60%. Optimising these methods generally requires expensive infrastructure and software upgrades. Alternatively, control systems such as unloading or blow-off systems are used to avoid compressor surge. Control systems adapt the inlet blow-off valve positions to sustain the minimum required flow and delivery pressure to operate within safe ranges [17], [78], [82], [83].

In 2017, Vermeulen et al. developed a new cost-effective control strategy for reducing the oversupply of compressed air. This strategy used existing infrastructure by retrofitting an existing square butterfly. An actuator with a positioner was installed on the existing butterfly valve. Guide vane control originally controlled the inlet air, while the butterfly valve could only be opened or closed as shown in Figure 24 [83].After installing an actuator and positioner, the butterfly valve was converted into a variable inlet throttle controller. As a result, the inlet air could be reduced further than the existing variable guide vane control allowed. This enabled the ESCO to minimise the load through the compressor when required. The surge margins were, however, revised to reduce the minimum allowable flow through the compressor [83].

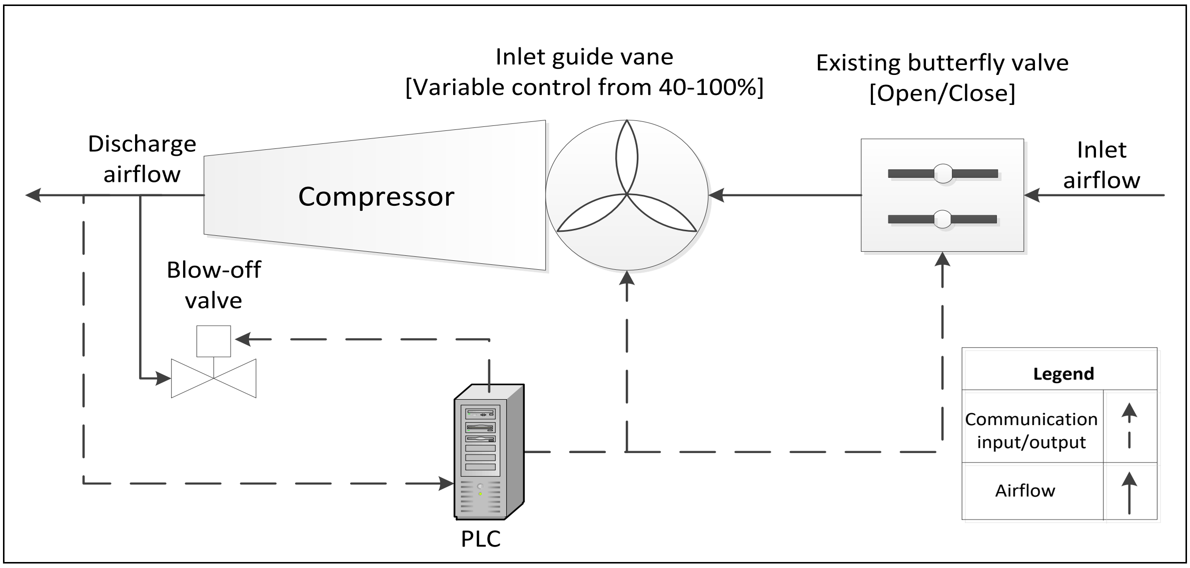


Figure 24: Typical air and communication flow of a centrifugal compressor (adapted from [83])

A previous energy saving project originally required improved compressor control on three baseload compressors. The system pressure was reduced when the air demand decreased. A daily saving of 1.07 MW was achieved due to the improved compressor control. One of the three baseload compressors alternated between the minimum and maximum inlet guide vane angles during cleaning shifts. A second compressor alternated between the loaded and off-loaded positions during the blasting period [17], [78].

Further optimisation was implemented on the three baseload compressors to reduce system pressures. As a result, a total power saving of 2.4 MW was achieved by optimising the compressor control [17], [78]. The optimised control reduced the system pressure to such an extent that one fewer compressor was required during low pressure demand periods. One of the three baseload compressors was thus stopped during low-demand periods. Thus, sufficient reduction in the compressed air demand or optimisation of compressed air supply could result in the shutdown of a compressor. Previous research found that more savings could be achieved by stopping a compressor than by operating at a reduced load [17].

2.6.3 *Optimised compressor selection*

An alternative method for optimising compressed air supply is improving compressor selections [84]. This section discusses typical compressor selection techniques previously used in energy saving strategies to optimise compressed air supply. This approach can be described by using studies conducted by Booysen and Marais. Figure 25 indicates a surplus of compressed air supply during specific times. A solution is to operate an optimised compressor combination. However, not all mines allow stopping and starting of compressors [17], [33], [78].

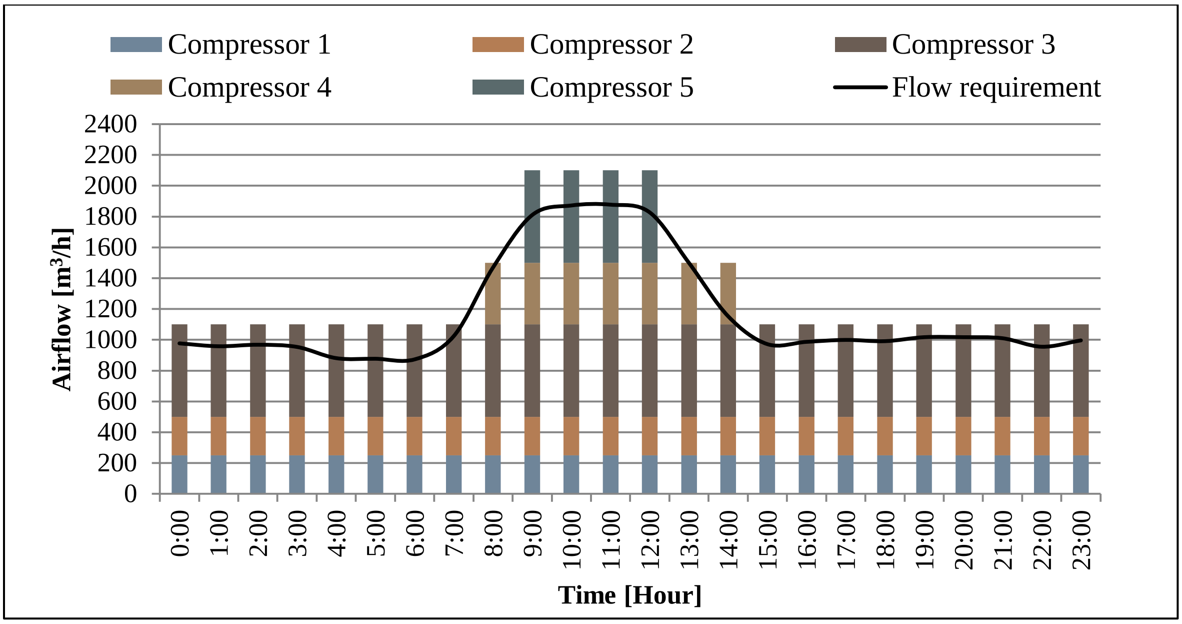


Figure 25: Inefficient compressor combination (adapted from [17])

A revised compressor combination was proposed to optimise the difference between the flow demand and supply. It was, however, found that oversupply still occurred. An assumption was made in this study that the existing compressor control could not throttle the air supply further. Another study was conducted to replace an oversized compressor with a smaller compressor. The original compressor configurations included three identical centrifugal compressors. These compressors were able to deliver up to 3 058 m^3/h at 862 kPa and could throttle to a minimum supply of 2 379 m^3/h using inlet control valves [17], [85].

The compressed air demand from this system was approximately 3 400 m^3/h during normal operating conditions. Thus, one compressor operating at maximum capacity would be insufficient. However, two compressors at minimum supply would generate an oversupply of compressed air. Energy savings could be realised by operating a smaller compressor to optimise the difference between the supply and demand during patterns of normal operations [17], [85]. The cost-effective control developed by Vermeulen et al. could be an alternative solution. The control used a combination of existing infrastructure and available control strategies to reduce the air supply of an oversized compressor further [83].

2.6.4 *Dedicated compressed air supply*

A compressed air system must be pressurised according to the demand of individual end users on the surface. Among these end users, processing plants is one of the largest air consumers. The processing plant requires the highest pressure demand on the surface. Therefore, for this example, the entire compressed air system had to be pressurised to satisfy the air requirements of the processing plant.

However, the surface pressure demand excluding the processing plant was relatively small. This highlighted the potential of supplying the plants with dedicated compressors to reduce the generation cost of compressed air. Simulations and tests were conducted, which indicated that an average energy saving 2 MWh could be achieved if a dedicated compressor was installed for the plants. Isolating and supplying end users according to specific requirements was thus identified as one strategy for optimising surface distribution control [17].

2.6.5 *Valve control on surface supply lines*

Another method used to control compressed air supply on surface is installing variable throttle valves on the surface supply lines. This valve enables reduced flow and pressures downstream from the valve during low-demand periods. Throttling the allowable airflow during low-demand periods results in a pressure build-up at the upstream side of the valve. As a result, compressor control reduces the pressure upstream of the valve, which leads to reduced generation cost. Thus, optimised supply control realises more savings when combined with surface valve control [81], [86], [87].

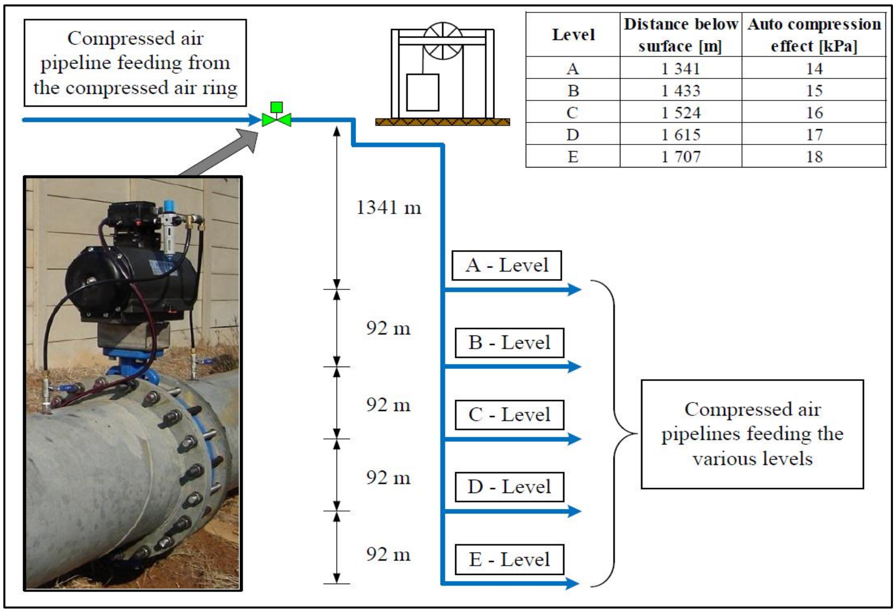
Several parameters need to be considered to control these valves accurately. This accurate information is required to implement valve control successfully. These valves are expensive and typically require infrastructure and software upgrades, which include integrated valve control strategies, communication networks, and sufficient instrumentation to measure key parameters. Monitoring key parameters enables mines to continuously monitor pressure and airflow in the compressed air supply lines. This important information can then be used to set up control schedules and pressure set points for each surface valve to optimise the supply and demand of compressed air [87].

2.6.6 *Compressed air demand control*

Mining activities occur at various depths (referred to as levels) within deep-level mines. New technologies enable mining to expand at greater depths with more feasibility. Compressed air supply lines distribute air from surface to underground as indicated in Figure 26. Initially, the air is transferred through a vertical pipeline down the shaft, from where it is distributed to horizontal levels. Each level can be installed with a dedicated control valve. The underground control requirements are similar to surface valve control.

The pressures losses at each level differ due to several elements that can affect the pressure delivered to different end users. These elements typically include different types of pneumatic equipment used underground, pressure losses over bends and valves, and friction in pipes [88].

Leaks underground and on the surface is one the largest contributors to pressure drops in supply lines. Auto-compression, however, occurs at deep levels as a result of the air weight. This phenomenon contributes to the compressed air pressure at deep levels [88].



Level	Distance below surface [m]	Auto compression effect [kPa]
A	1 341	14
B	1 433	15
C	1 524	16
D	1 615	17
E	1 707	18

Figure 26: Compressed air distribution from surface to underground [81]

2.6.7 *Leak repair on air supply lines*

An air leak can be defined as any opening where compressed air is unintentionally, or without authority, released into the atmosphere. Excessive air leaks can cause pressure losses of 20–30% in the air supply lines leading to the end users. The result is that energy cost increases as compressed air generation has to accommodate these pressure losses. Energy savings can be realised by repairing air leaks on compressed air systems [81], [86], [87], [89].

Locating, recording and fixing all the leaks on underground supply lines is a time-consuming exercise. A quick method of solving this problem is isolating the problem sections by installing open/close isolating valves on the airlines feeding these problem sections. The air flowing through that section can be restricted, thus allowing the air pressure in the rest of the air system to be maintained at the required pressure [81], [86], [87], [89].

2.7 **Integrated approaches to select strategies**

2.7.1 *Overview*

Marais evaluated several case studies during his study. He found that deep-level mines only focus on specific energy saving techniques to optimise compressed air systems. Energy saving strategies do not use integrated approaches to optimise energy savings across the whole compressed air system. Marais summarised the techniques used across 11 different deep-level mines [17].

Numerous energy saving techniques typically used on deep-level mines have been discussed in this chapter. These techniques include both supply- and demand-side optimisation. IDM-funded projects were implemented as energy saving initiatives based on the old project-based ESCO model, which allowed attractive budgets for energy saving initiatives. Previous research found that mines implement energy saving strategies as a single solution. Thus, there is a need for an integrated approach that combines these different strategies to optimise the entire compressed air system.

In 2012, Marais developed an integrated approach to combine existing energy saving strategies. This integrated approach is summarised in Figure 27. It is claimed that the integrated approach was implemented on 22 compressed air systems of different mines. As a result, an estimated average power saving of 109 MW was achieved. The cost of the total project was R795 million, which amounts to R7.3 million per megawatt. Marais estimated that these project costs would be recovered within 12 months by including both the old IDM model funding and electricity cost savings as a result of the energy saving initiatives [17].

This section discusses three previous case studies from the 22 projects implemented by Marais to analyse the approach used in different mines. The aim is identifying the shortfalls of these available methods for selecting best-suited strategies to realise potential savings.

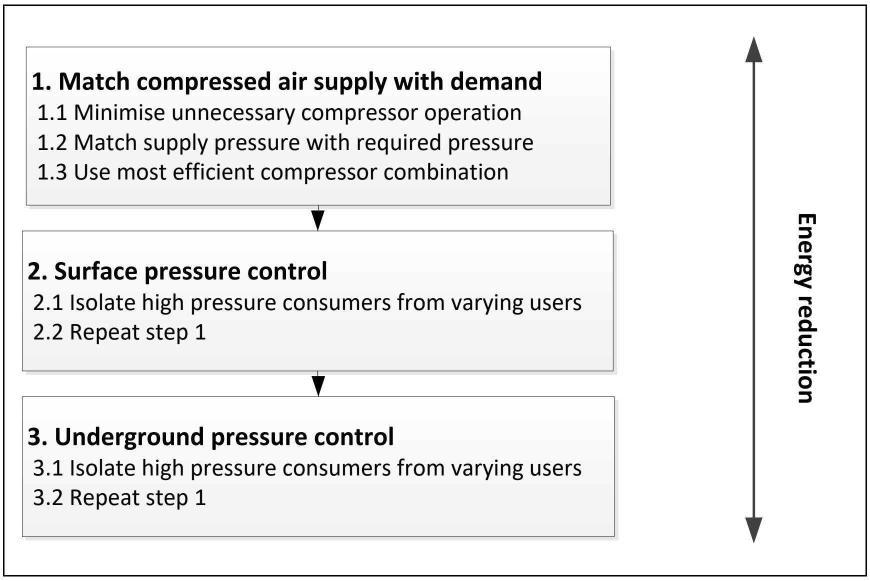


Figure 27: Available integrated approach for realising potential energy savings (adapted from [17])

2.7.2 Previous DSM project 1

Overview

Marais discussed some case studies on mines that used his integrated approach to reduce power consumption on compressed air systems. In 2009, Marais conducted a DSM project on a mine that had five compressors that supplied air to three shafts [17].

Marais required multivariable data sets to conduct the integrated approach developed in his study. This data included compressor power and system pressure data. Based on the integrated approach, the first step was matching air supply and demand. All the compressors already had inlet control valves. However, it was found during the investigation that the existing control was fixed at a set point of 600 kPa although the actual system pressure never reached that set point (see Figure 28).

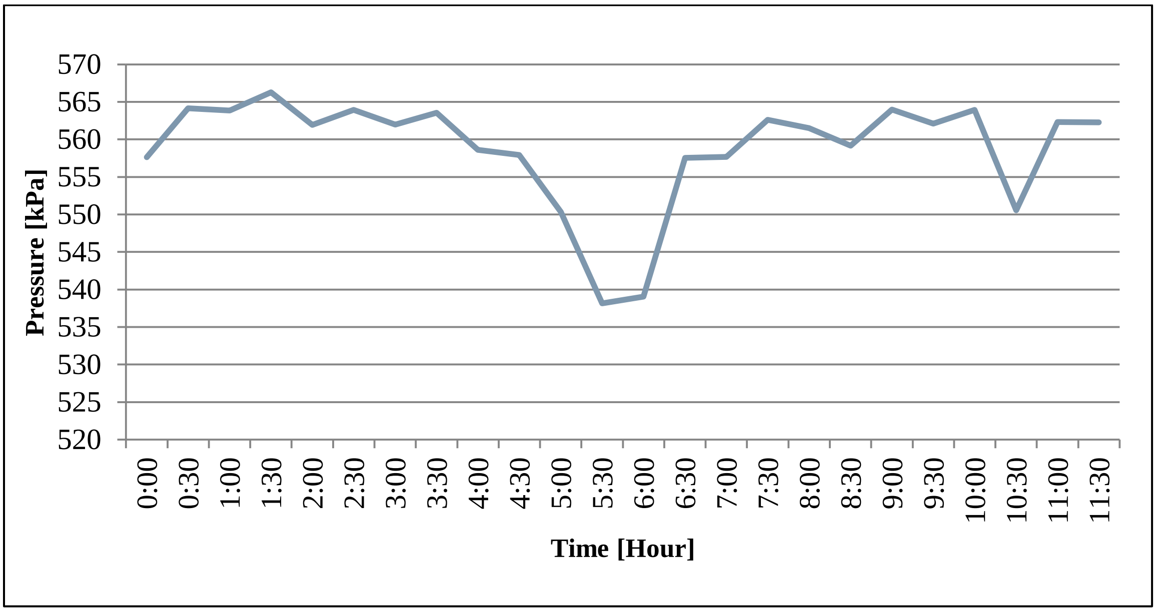


Figure 28: Actual system pressure in DSM project 1 (adapted from [17])

The air and pressure demand from all critical pneumatic equipment was identified, which enabled the mine to identify actual air requirements and areas of oversupply [17]. Loaders, loading boxes and rock drills demanded the highest pressure requirements. This equipment was mainly used during drilling shifts between 07:00 and 15:00. However, refuge bays and agitation constantly required compressed air throughout the whole mine operation schedule [17].

Realise potential energy savings on DSM project 1

After in-depth data analysis and detailed audits, mine personnel were made aware that the existing pressure supply was higher than required. The mine agreed that these pressures should be lowered. The mine approved a delivery pressure of 550 kPa during drilling shifts and 490 kPa during non-drilling shifts. Marais then used a simplified simulation tool that he developed in 2012 to quantify the potential savings by lowering the system pressure. In 2009, the simulating model estimated a saving of 0.9 MW based on the new pressure set points [17].

The investigation was repeated in 2010 to verify the actual data used. Thus, power consumption data was recollected in 2010 to populate the simulation. However, system pressure data was not available during this period. This highlights the need for a tool to quantify potential savings without multivariable data sets. Power usage is typically readily available opposed to data such as pressure, flow and production [17].

Due to unavailable pressure data in 2010, Marais assumed that the consumption was similar to 2009. The simulation model was thus populated with the system pressure of 2009 and the power consumption of 2010. Previous research showed that these types of estimation could result in inaccurate power saving estimations. The new results showed that an estimated 0.98 MW saving could be achieved by adapting the existing pressures to the proposed pressures [17].

The simulation results were verified with a saving of 0.97 by manually reducing the system pressure set points as discussed with mine personnel during a manual test. Thus, the simulation was verified. As a next step, a new project was then implemented that optimised the compressor control to automatically adjust the system pressure during different demand schedules [17]. After implementing the automatic control, the new power consumption compared with the baseline showed a saving of 1.7 MW (see Figure 29).

Marais assumed that the increase in savings was due to possible leak repairs during the implementation of the new compressor control. It is not clear from the study whether the next steps of the integrated approach were followed [17]. However, the additional savings were not predicted with the existing simplified tool.

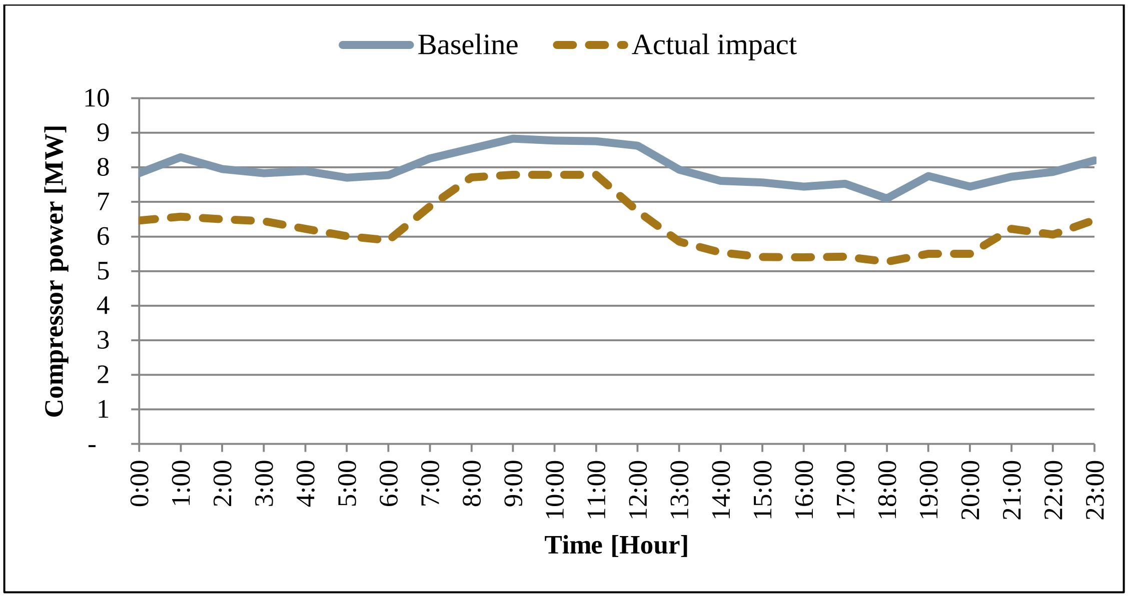


Figure 29: Savings impact after implementing an integrated approach to DSM project 1

2.7.3 *Previous DSM project 2*

Overview

DSM project 2 included a mine that operated three baseload compressors that were not allowed to be stopped or started frequently. This mine had existing underground control valves implemented. The baseline power and pressure consumption profiles used in DSM project 2 are shown in Figure 30. The system pressure during drilling shifts was lower than during the non-drilling shifts.

Previous studies highlighted potential energy savings during non-drilling shifts in such a scenario. As a first step, Marais further investigated the airflow supply and airflow demand. This corresponded with the first step within the integrated approach developed by Marais [17].

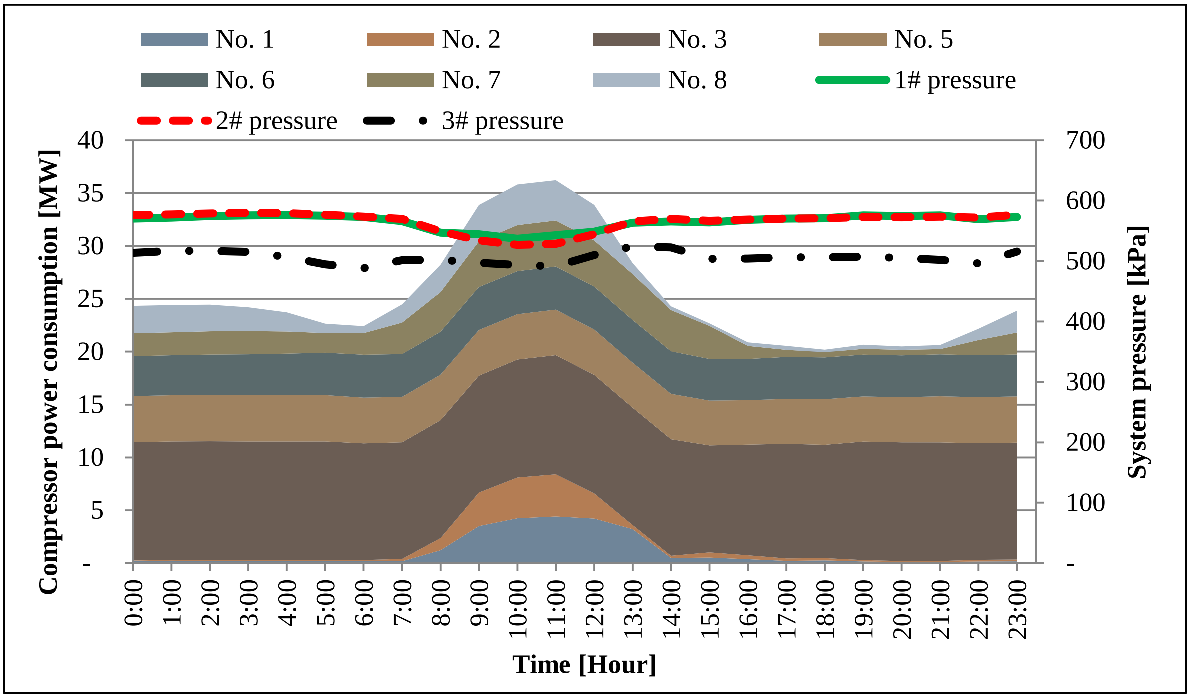


Figure 30: Baseline pressure and power consumption profiles in DSM project 2 [17]

Achieving potential energy savings on DSM project 2

Data analysis proved that the required air demand could be matched after implementing the integrated approach developed by Marais. Simulations were used to quantify these potential energy savings. These simulations showed that a saving of between 2.2 MW and 2.6 MW could be achieved. However, in combination with the improved compressor control, the enhanced surface and underground air distribution control achieved an average saving of 2.8 MW [17].

Further investigations found that the compressed air systems supplied processing plants. However, a dedicated compressor was located at the plant. This compressor was only used as a backup compressor and not on a regular basis. A simulation indicated that one of the baseload compressors could be stopped if the compressor at the plant was allowed to operate during normal operations [17]. Thus, these savings could increase from 2.8 MW to 5 MW if the compressor at the plant was allowed to operate during normal operations. Manual tests were conducted, which verified that the plant compressor could realise a saving of 4.5 MW. The actual saving was thus 500 kW (10%) less than the estimated savings calculated with the simulation [17].

2.7.4 Previous DSM project 3

Overview

DSM project 3 includes a mine that had 12 compressors that supplied air to eight different shafts. This mine consisted of several workshops, pneumatic systems and a large number of underground working areas. The integrated approach was implemented. The first step was matching the compressed air supply with the demand. The power consumption and pressure profile baseline are shown in Figure 31.

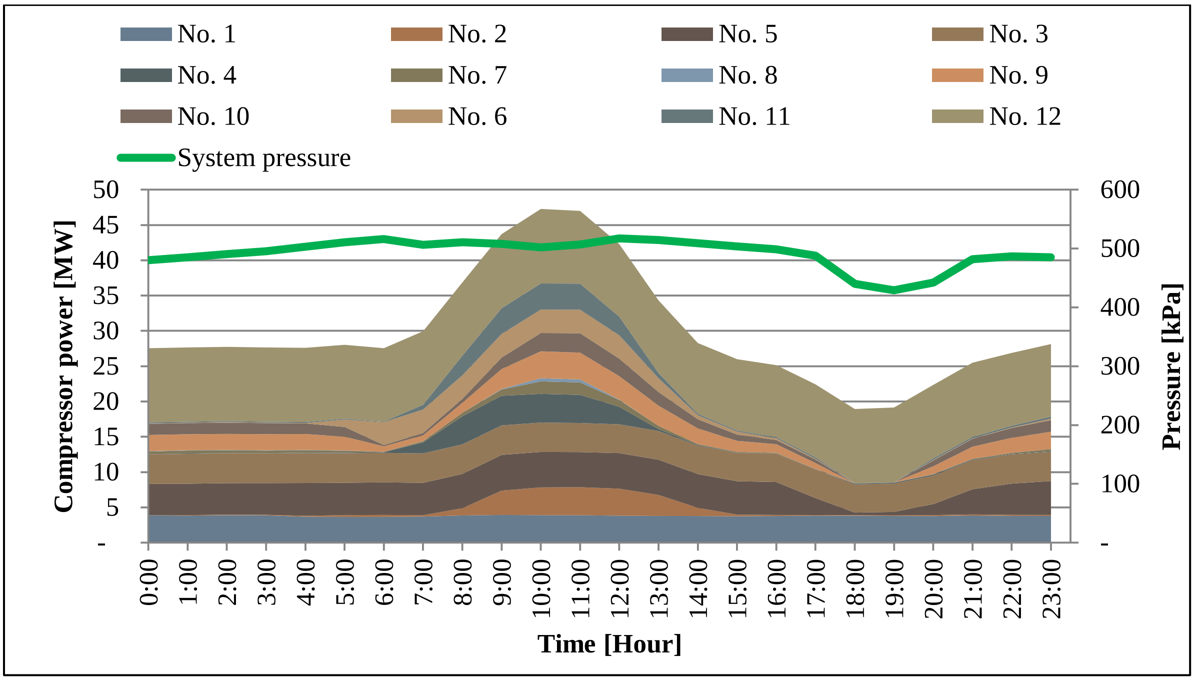


Figure 31: Baseline demand of compressed air system used in DSM project 3

This mine approved frequent stopping and starting as a control mechanism for optimising the supply side of the compressed air system. Thus, the control room operators could manually stop and start compressors from a central control room to match the supply with the demand side. The second step in the integrated approach was controlling the surface air distribution [17].

Existing valves could be used to control the air demand while satisfying minimum pressure requirements for different end users. In this case, required data sets were unavailable and detailed simulation models could not be performed. Thus, Marais used a simplified simulation model to estimate potential savings after implementing and improving the control on surface valves [17].

Realising potential energy savings in DSM project 3

This simplified model required data sets, which included pressure and power consumption, to estimate a saving of 4.0 MW. If high-pressure end users were supplied with a dedicated air supply, the projected savings could increase. The simplified simulation indicated that a saving of 4.9 MW could be achieved by isolating high-pressure consumers. After implementing the integrated approach by isolating high-end users, an energy saving of 5.7 MW was realised. Marais was thus accurate within 15% of the actual savings.

2.7.5 Expanded development on existing integrated approach

In 2014, Van der Zee derived an integrated approach from the approach developed by Marais [33]. Van der Zee identified that Marais did not include steps to rate mines based on the scope for potential savings. Thus, Van der Zee further developed Marais approach to identify mines with potential scope for implementing the integrated strategy.

The first step added to Marais's strategy was collecting data for benchmarking. The second additional step added by Van der Zee was rating mines according to scope for potential improvement. Thus, the additional steps added an identification phase to Marais's approach (see Figure 32).

However, Van der Zee required multivariable data sets to benchmark and compare different mines. The benchmarking method was developed on selected gold mines that had the required data sets available. These data sets are not always readily available, and in some cases it is not practical to collect the required data from the site [17], [33].

Simulation models were also used to quantify potential savings as seen from the simulation procedure provided by Kriel in Figure 23 [81].The third step in Van der Zee's integrated approach realised potential energy savings by using the integrated approach originally developed by Marais. Best-suited strategies were then selected from the findings of simulations and detailed audits [17], [33].

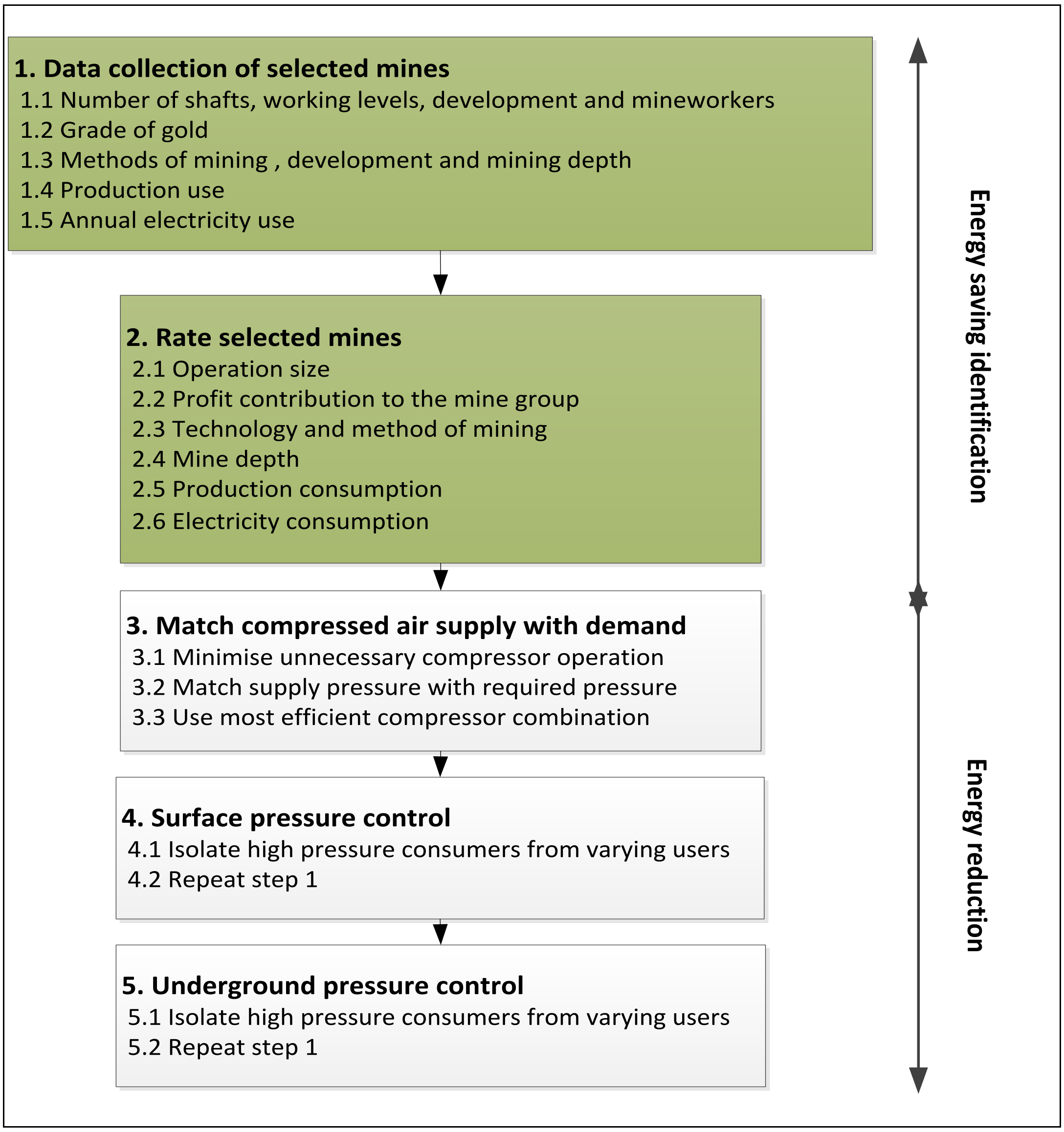


Figure 32: Available integrated strategy procedure developed by Van der Zee (adapted from [17])

2.8 Conclusion

This section consisted of several studies previously conducted during an investigation of energy projects. Previous studies highlighted that investigations demand time, resources and skills. Some familiar approaches used during investigations include benchmarking and saving identification tools. Benchmarking is used to rate the performance of energy systems while saving identification tools are used to quantify potential energy savings.

However, these existing approaches have several shortfalls, which create the needs summarised in Table 13. Time-consuming and labour-intensive audits are typically conducted to acquire necessary multivariable data sets for the investigation techniques currently used. This could lead to prolonged investigation periods, which negatively affect the feasibility the projects for ESCOs.

Table 13: Summary of needs identified from the critical review

<table>
<tr><th>A NEED EXISTS FOR A BENCHMARKING METHOD TO RANK COMPRESSED AIR SYSTEMS THAT …</th><th>A NEED EXISTS FOR A TOOL TO QUANTIFY POTENTIAL ENERGY SAVINGS THAT …</th></tr>
<tr><td colspan="2">• Do not require multivariable data sets including production, pressures and flows.
• Use minimal variables, which are readily available, and verifiable data.
• Consider power consumption profiles of compressed air systems.
• Considers deep-level mines of all depths.
• Can be used on one specific mine or a combination of mines.
• Require minimal resources
• Deliver time-efficient results.
• Deliver results within acceptable accuracies.</td></tr>
</table>

Previous studies indicated that several strategies for achieving potential energy savings on compressed air systems are available. These strategies can be used to realise energy savings within energy efficiency or load clipping initiatives. Marais and Van der Zee developed integrated approaches to identify best-suited strategies to realise energy savings within energy efficiency and load clipping initiatives.

These existing integrated approaches were implemented during a time period where sufficient funding was available to motivate energy saving initiatives. Therefore, ESCOs could risk the resources required to investigate new potential energy saving projects. However, current economic conditions and financial constraints necessitate simplified methods that reduce the risks and input required to investigate new potential energy saving projects.

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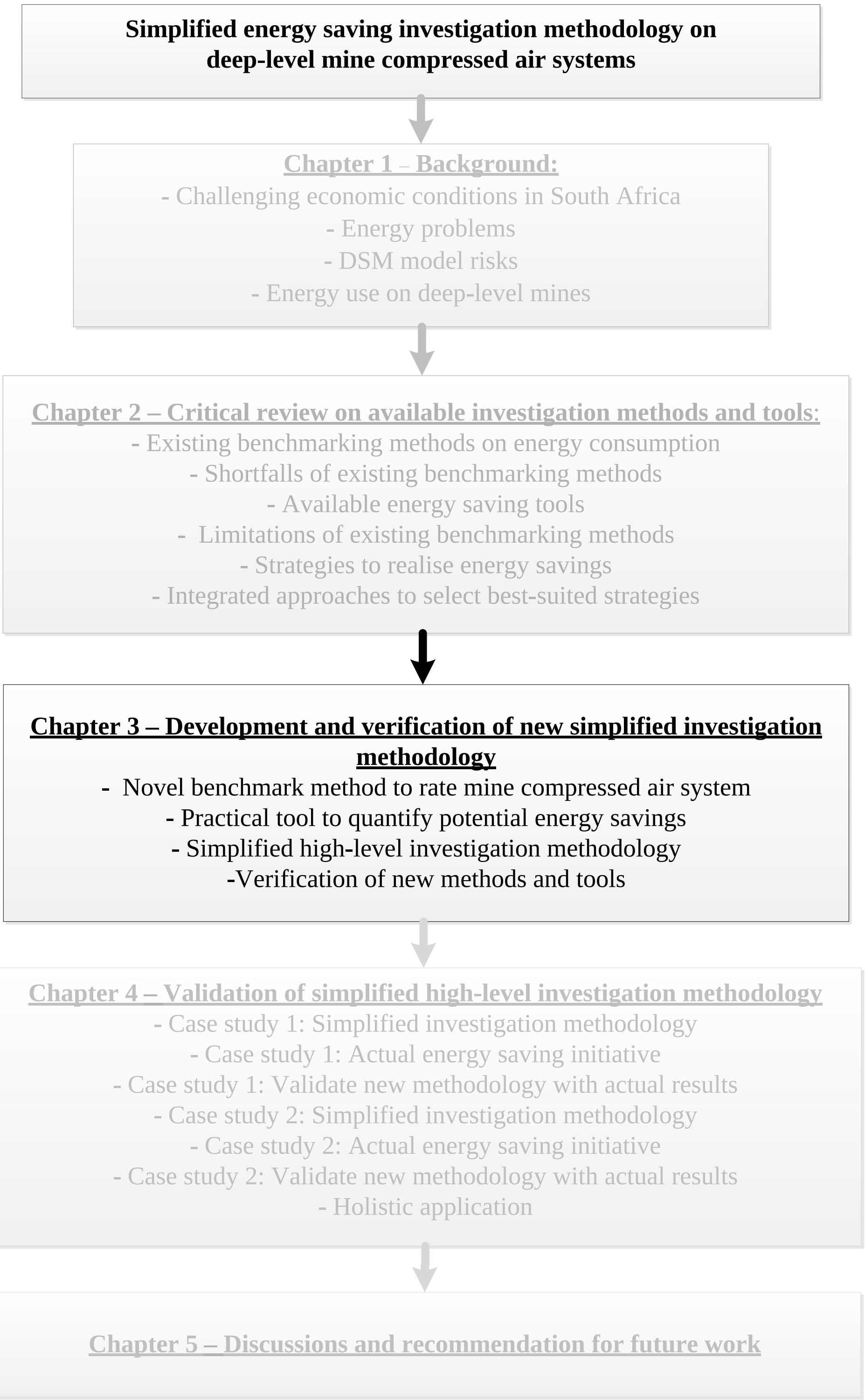
3 DEVELOPMENT AND VERIFICATION OF A NEW SIMPLIFIED INVESTIGATION METHODOLOGY



Simplified energy saving investigation methodology on deep-level mine compressed air systems

Chapter 1 – Background:
- Challenging economic conditions in South Africa
- Energy problems
- DSM model risks
- Energy use on deep-level mines

Chapter 2 – Critical review on available investigation methods and tools:
- Existing benchmarking methods on energy consumption
- Shortfalls of existing benchmarking methods
- Available energy saving tools
- Limitations of existing benchmarking methods
- Strategies to realise energy savings
- Integrated approaches to select best-suited strategies

Chapter 3 – Development and verification of new simplified investigation methodology
- Novel benchmark method to rate mine compressed air system
- Practical tool to quantify potential energy savings
- Simplified high-level investigation methodology
- Verification of new methods and tools

Chapter 4 – Validation of simplified high-level investigation methodology
- Case study 1: Simplified investigation methodology
- Case study 1: Actual energy saving initiative
- Case study 1: Validate new methodology with actual results
- Case study 2: Simplified investigation methodology
- Case study 2: Actual energy saving initiative
- Case study 2: Validate new methodology with actual results
- Holistic application

Chapter 5 – Discussions and recommendation for future work

3.1 Preamble

Shortfalls of existing methods and tools used during typical investigation processes were identified in Chapter 2. Thus, the need for new methods and tools was identified. This chapter focuses on developing new methods and tools that accommodate the shortfalls identified in Chapter 2.

The first objective of this study as stated in Chapter 2 is simplifying current methods and tools used during typical investigation processes on energy saving projects. The second objective of this study is integrating the simplified methods and tools of Objective 1 to develop a new simplified high-level investigation methodology. This new investigation methodology will enable ESCOs to minimise risk and resources required during investigations of new energy saving initiatives. This chapter focuses on developing new methods and tools to achieve the above-mentioned objectives by considering the background and critical review from Chapter 1 and Chapter 2.

For Objective 1, the first step is developing a new single-variable benchmarking model that only requires energy consumption data as an input. This will reduce the risk and input required during investigations to rate compressed air systems according to scope for improvement. The second step is creating a new simplified single-variable tool that quantifies potential savings on compressed air systems. Ultimately for the second objective, Step 1 and Step 2 are combined to compile a new simplified high-level investigation methodology.

3.2 A novel benchmarking method for ranking compressed air systems

The first step of this chapter is developing a new benchmarking method in view of the shortfalls identified for existing benchmarking methods. A need was identified for a new benchmarking method that uses single-variable and readily accessible data sets. Electricity consumption has been the common dependent variable used during the literature study and is available from most mines. Thus, electricity use is considered readily accessible.

Previous research also highlighted the need to investigate the relation between compressed air energy consumption and mining shifts further. High-demand periods for compressed air are typically indicated in compressed air profiles during the drilling shifts and low-demand periods during blasting shifts. Figure 33 shows the typical power consumption profile of deep-level mine compressed air systems during different mining shifts.

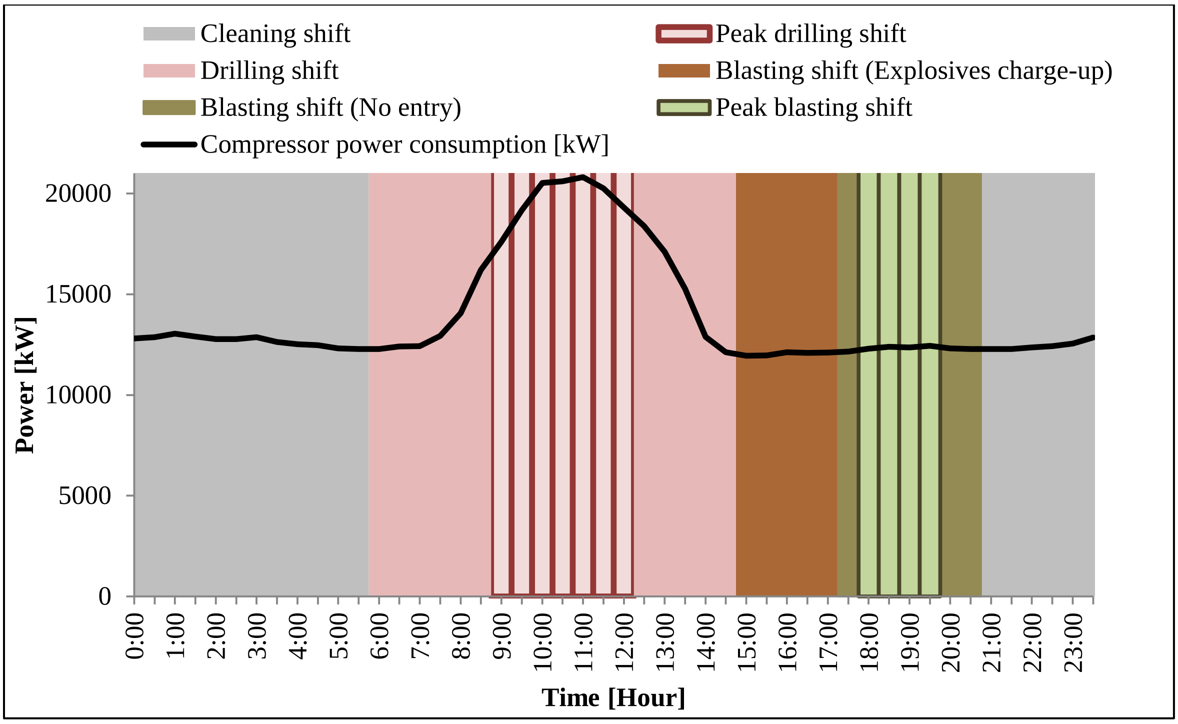


Figure 33: Illustration of the peak drilling and Eskom periods during normal operations

Previous studies considered the peak drilling shift to be between 09:00 and 13:00. This could differ for specific mines and should be considered when calculating the average power consumption during peak drilling shifts. The power consumption is expected to be the highest during the peak drilling shift due to maximum air demands. This will be further referred to as the peak drilling shift. The blasting shift is normally within Eskom's evening peak period. During blasting shifts, the air demand should be the lowest. This period will be further referred to as the peak blasting shift. The power consumption difference between the peak drilling shift and the peak blasting shift should have the largest energy consumption difference among the different schedules. This energy difference will be further referred to as the energy reduction ratio (ERR).

The pressure supply set point during the drilling shift is normally set to operate without limitations. However, previous research in Chapter 2 indicated that mines often oversupply air during non-drilling shifts. Therefore, significant potential exists to reduce the air supply during blasting shifts. Various energy saving projects have thus been implemented in the past to reduce the generation costs and air demand during non-drilling shifts. The focus of the new benchmarking method is to rate the ERR between the highest air demand period (peak drilling shift) and lowest air demand period (peak blasting shift).

Actual baseline and performance assessment data was collected for this study from 25 DSM projects previously implemented on platinum and gold mine compressed air systems. Both the baseline and performance assessment data sets consist of the average power consumption over a three-month period.

An independent M&V team appointed by Eskom, as previously discussed in Chapter 1, verified the baseline and performance assessment data. The baseline data sets can be used to determine the ERR of compressed air systems before implementing energy saving projects (pre-implementation data). ESCOs will be able to rank compressed air system efficiencies based on the ERR between the maximum and minimum air demand periods. This will indicate how efficiently mines can reduce compressed air generation from peak drilling shifts to peak blasting shifts. The ERR can be calculated by using Equation 2.

$$\left(1-\frac{b}{d}\right)\times 100=\mathrm{ERR}_{(Pre)} \tag{2}$$

Where:

b = Average power consumption during peak blasting shift [MW]

d = Average power consumption during peak drilling shift [MW]

$\mathrm{ERR}_{(Pre)}$ = Pre-implementation energy reduction ratio [%]

The peak blasting shift power consumption during the performance assessment periods will be used to determine the ERR of compressed air systems after implementing energy saving projects (post-implementation). After implementation, the typical oversupply during non-drilling shifts should be reduced. Thus, the ERR is anticipated to increase after reducing the power generation during non-drilling shifts.

The ERRs of 25 mines, which included gold and platinum mines, were determined. These include mines of various depths ranging from an estimated 0.5 km to 4 km. The ERRs before and after implementation of energy saving projects were determined for each compressed air system. Table 14 shows the result after determining the ERRs of these 25 compressed air systems. The pre-implementation ERRs of previous energy saving initiatives on compressed air systems were calculated with the baseline data collected for these systems. The post-implementation ERRs were determined by using a combination of the peak drilling power consumption from the baseline data, and the peak blast shift data from the performance assessment data.

The results given in Table 14 are plotted in Figure 34. The average existing ERR before implementing energy saving projects was determined to be 25%. This is considered as the average benchmark ERR on deep-level mine compressed air systems. The ERRs of Mine 1 to Mine 11 are below the average benchmark ERR. Mine 12 is on the average benchmark ERR, while Mine 13 to Mine 25 are above the average benchmark ERR. The average ERR increase for Mine 1 to Mine 11 is 22%. This is 9% less than the average ERR increase of Mine 13 to Mine 25, which is 13%. It can be assumed that mines with pre-implementation ERRs below the average benchmark ERR have more scope for potential savings than mines with ERRs larger than the average benchmark ERR.

Thus, the ERRs of mines before implementation of energy saving projects can be compared with the average benchmark ERR of 25%. This will enable ESCOs and mines to rank compressed air systems according to potential scope for improvement with only power consumption as an input.

Table 14: ERR results of 25 deep-level mine compressed air systems

MINE	PRE-IMPLEMENTATION			POST-IMPLEMENTATION		
	AVERAGE POWER USAGE DURING PEAK DRILLING SHIFT 09:00–12:00 [MW]	AVERAGE POWER USAGE DURING PEAK BLASTING SHIFT 18:00–20:00 [MW]	ERR %	AVERAGE POWER USAGE DURING PEAK BLASTING SHIFT 18:00–20:00 [MW]	ERR %	ERR INCREASE %
1	6.60	6.91	−5	5.35	19	24
2	8.53	8.54	0	5.80	32	32
3	11.20	11.06	1	8.90	21	19
4	31.61	29.94	5	21.94	31	25
5	15.39	14.42	6	12.09	21	15
6	11.52	10.64	8	7.77	33	25
7	40.90	35.37	14	24.27	41	27
8	15.25	13.18	14	10.10	34	20
9	8.76	7.42	15	5.38	39	23
10	8.80	7.14	19	5.64	36	17
11	18.22	14.68	19	12.15	33	14
12	13.84	10.41	25	7.73	44	19
13	34.93	25.39	27	21.88	37	10
14	13.52	9.73	28	8.41	38	10
15	24.78	17.57	29	13.16	47	18
16	35.60	23.86	33	15.89	55	22
17	17.71	11.09	37	8.94	50	12
18	19.76	12.38	37	10.25	48	11
19	59.63	36.79	38	33.13	44	6
20	20.99	12.82	39	8.33	60	21
21	24.86	14.63	41	11.39	54	13
22	24.46	14.39	41	11.02	55	14
23	12.37	6.42	48	5.29	57	9
24	13.04	6.56	50	4.81	63	13
25	11.68	4.90	58	4.15	64	6
Min	**6.60**	**4.90**	**−5**	**4.15**	**19**	**6**
Avg.	**20.16**	**14.65**	**25**	**11.35**	**42**	**17**
Max	**59.63**	**36.79**	**58**	**33.13**	**64**	**32**

The minimum, average and maximum benchmark ERR increase after implementing energy saving initiatives on compressed air systems are shown in Table 15.

Table 15: Expected minimum, average and maximum benchmark increase

DESCRIPTION	ERR INCREASE [%]
Benchmarked minimum ERR increase	6%
Benchmarked average ERR increase	17%
Benchmarked maximum ERR increase	32%

The ERR increase ranges of each compressed air system from the mines considered in Table 14 are indicated in Figure 34. Of the mines that operated below the average benchmark ERR of 25%, a total of 83% achieved an ERR increase above the average expected benchmark increase of 17%. Of the mines that operated above the average benchmark ERR of 25%, a total of 83% had an ERR increase below the average expected benchmark increase of 17%. Thus, it can be concluded that compressed air systems that operate below the average benchmark ERR of 25% have more potential for improvement than mines that operate above the average ERR.

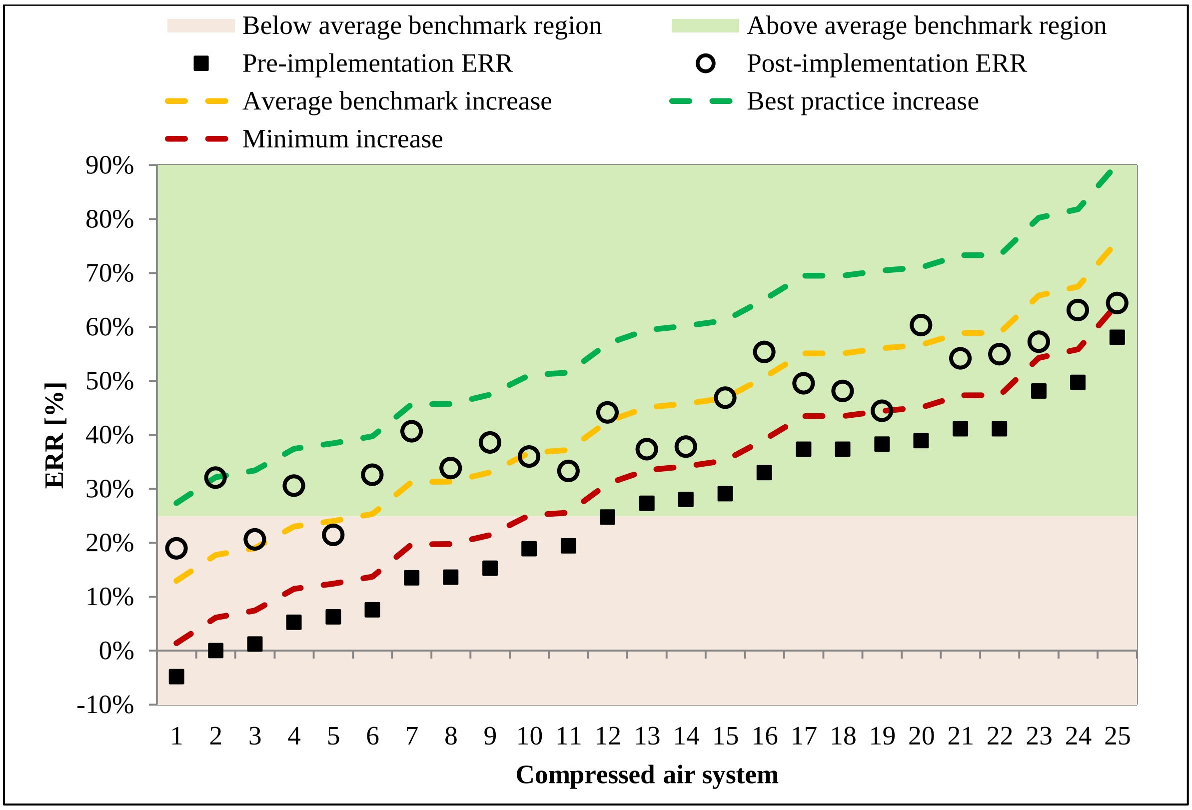


Figure 34: Novel benchmarking method for rating deep-level mine compressed air systems

The benchmarking method developed in this section is verified in Section 3.5. Figure 35 summarises the methodology process required to benchmark and rank specific compressed air systems according to scope for improvement. By considering the estimated minimum, average and maximum ERR increases, ESCOs are able to project the available scope for improvement on compressed air systems. This method only requires energy consumption data (single-variable input) to conduct this new simplified benchmarking process (as shown in Figure 35). The solution serves as Contribution 1 and can be discussed as follows:

1) With limited data, time and resources available, the new simplified benchmarking method can be used to rank compressed air system according to scope for improvement.

1.1) The simplified method only requires power consumption data of the maximum power demand (peak drilling shift) and minimum power demand (peak blasting shift) periods. Therefore, an ESCO only has to collect available energy consumption data of the existing compressed air system operation.

1.2) The pre-implementation ERR can be calculated with Equation 2 with the average maximum (d) and average minimum (b) power demand periods as inputs.

1.3) The scope for improvement is more than average if the pre-implementation ERR is less than 25%. Thus, there is less scope than average should the pre-implementation ERR be greater than 25%.

1.4) If the scope for improvement is more than average, it is more likely that the ESCO will achieve the savings target above the average expected benchmark increase.

1.5) The next step is quantifying the potential energy savings target of the compressed air systems identified in Step 1.4.

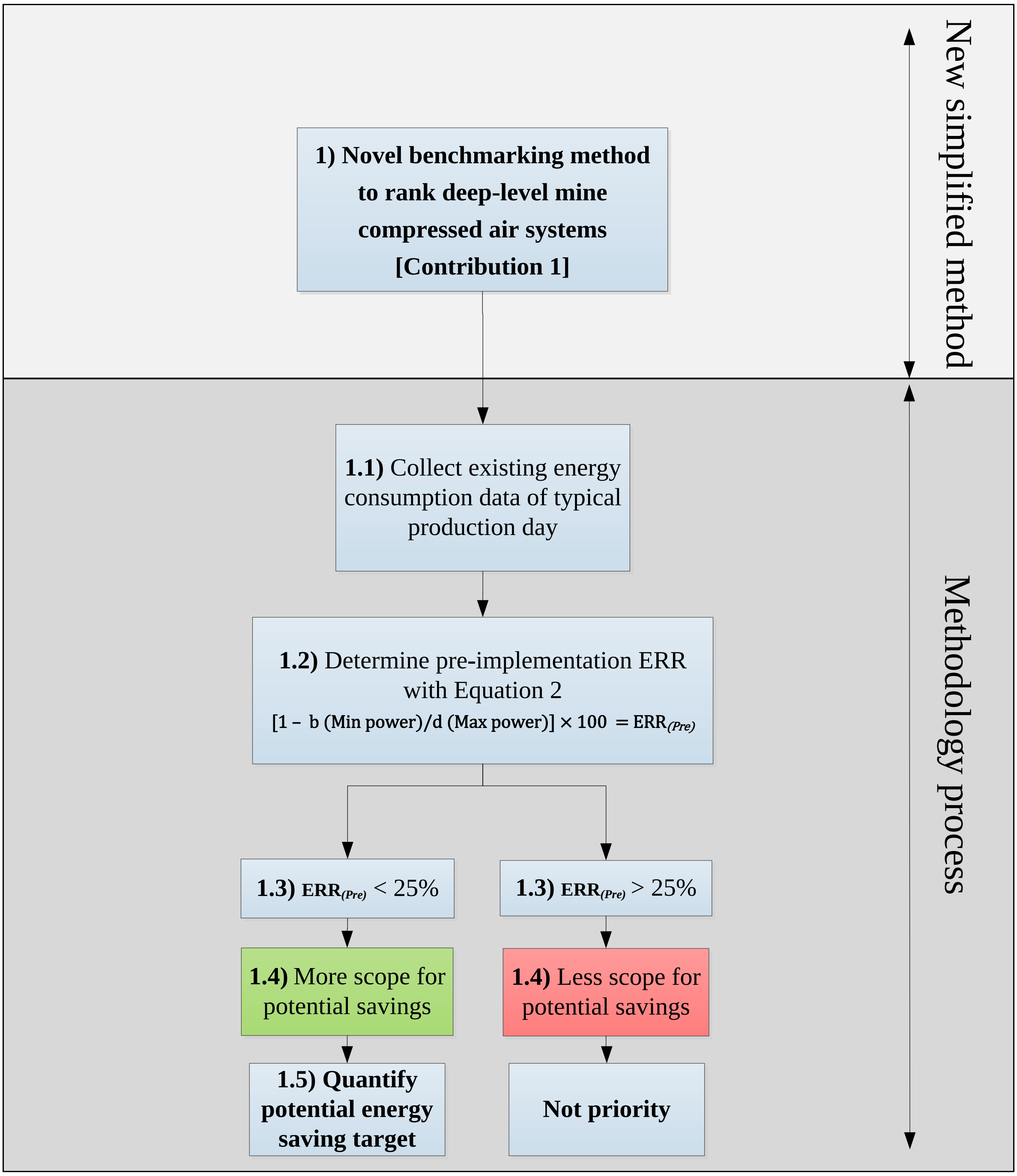


Figure 35: Methodology process to rate compressed air systems

3.3 A practical tool for quantifying potential energy savings

3.3.1 Overview

The new benchmarking method developed in the previous section could be used to rate compressed air systems according to their potential scope for improvement. Considering the shortfalls of existing tools for determining potential energy saving targets, the second step of this methodology chapter is developing a new practical tool for quantifying potential savings with only power data as a single-variable input. In this section, three tools are developed to predict the expected benchmark ERR increase, and one tool to estimate the potential energy savings target.

3.3.2 Three tools for estimating expected benchmark savings

Based on the benchmarking method developed in Section 3.2, the average expected ERR increase is 17% after implementing 25 energy saving initiatives. This average benchmark ERR increase can be used to predict the average expected potential savings on compressed air systems by using Equation 3.

$$b - [d - ((ERR_{(Pre)} + ERRI_{(Avg)}) \times d)] = T_{Avg} \tag{3}$$

Where:

b = Average power consumption during peak blasting shift [MW]

d = Average power consumption during peak drilling shift [MW]

$ERR_{(Pre)}$ = Pre-implementation ERR [%]

$ERRI_{(Avg)}$ = Benchmarked average ERR increase [%]

T_{Avg} = Average expected benchmark savings [%]

By using Equation 4, the minimum expected benchmark savings on compressed air systems can be estimated. This is based on the minimal benchmark ERR increase (6%) determined after implementing 25 energy saving initiatives. Thus, the second tool is estimating the minimum expected benchmark savings with Equation 4.

$$b - [d - ((ERR_{(Pre)} + ERRI_{(Min)})) \times d)] = T_{Min} \tag{4}$$

Where:

b = Average power consumption during peak blasting shift [MW]

d = Average power consumption during peak drilling shift [MW]

$ERR_{(Pre)}$ = ERR pre-implementation of energy saving projects [%]

$ERRI_{(Min)}$ = Benchmarked minimum ERR increase [%]

T_{Min} = Minimum expected benchmark savings [%]

The maximum potential savings can be estimated with the third tool shown (see Equation 5). This is based on the best practice ERR increase (32%) among 25 different compressed air systems identified with the benchmarking method developed in Section 3.2.

$$b - [d - ((ERR_{(Pre)} + ERRI_{(Max)}) \times d)] = T_{Max} \tag{5}$$

Where:

b = Average power consumption during peak blasting shift [MW]

d = Average power consumption during peak drilling shift [MW]

$ERR_{(Pre)}$ = ERR pre-implementation of energy saving projects [%]

$ERRI_{(Max)}$ = Benchmarked maximum ERR increase [%]

T_{Max} = Maximum expected benchmark savings [%]

3.3.3 *A tool for estimating the potential energy savings target*

Previous studies indicated the effectiveness of regression models when compared with other complex models such as simulations. However, previous regression methods required multivariable data sets. A need exists for a regression model that only requires power consumption as a single variable. Thus, a fourth tool is developed by using a regression model. In this model, the pre-implementation ERR of energy saving projects is the dependent variable on the X-axis. The post-implementation ERR is considered as the independent variable on the Y-axis. However, electricity usage remains the only required input variable.

Figure 36 shows the regression model developed for this study with the data previously shown in Section 3.2, Table 14. This model consists of the pre- and post-implementation ERRs from 25 compressed air systems previously discussed in Section 3.2. As seen in Figure 36, an R^2 of 0.87 was obtained for compressed air systems with an ERR that ranged between −5% and 58%.

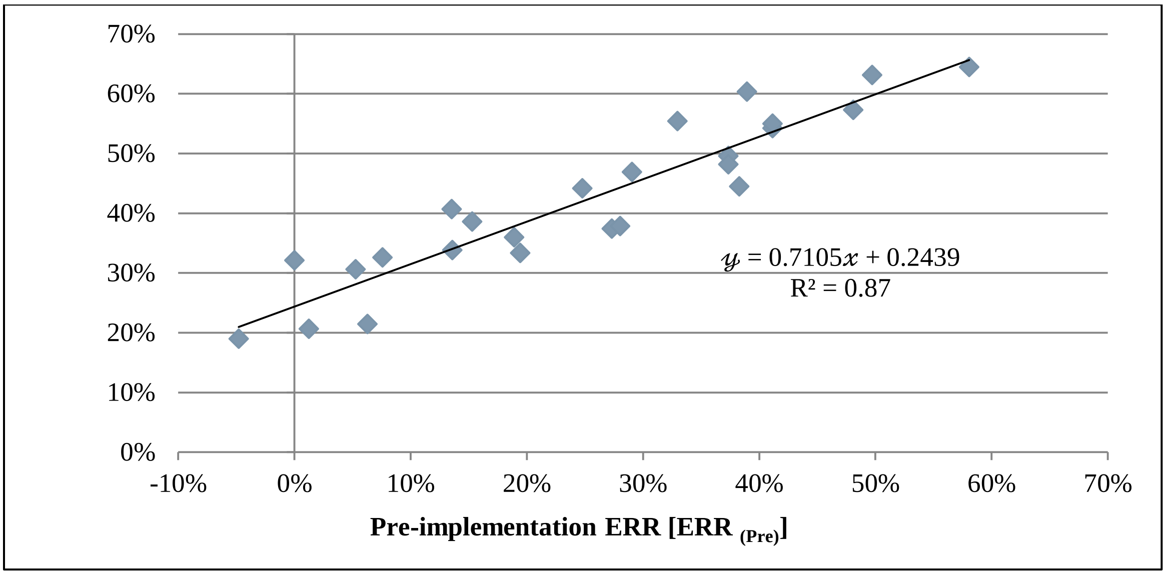


Figure 36: ERR regression model of deep-level mine compressed air systems

A significant positive relationship was found between the pre- and post-implementation ERR for a p-value smaller than 0.001. Thus, the regression model can be used to predict the post-implementation ERR of energy saving projects with a confidence level of at least 95%. This regression model introduced Equation 6:

$$y = 0.7105x + 0.2439 \qquad (6)$$

Where:

x = Calculated pre-implementation ERR [%]

y = Predicted post-implementation ERR [%]

The regression model shown in Figure 36 can be used to estimate the post-implementation ERR of new potential energy saving projects. Thus, the potential energy savings target of a compressed air system can be estimated by multiplying the expected post-implementation ERR determined by the regression model with the peak drilling shift power consumption. This can be achieved with Equation 7:

$$b - [d - (ERR_{(Reg)} \times d)] = T_{Est} \qquad (7)$$

Where:

b = Average power consumption during peak blasting shift [MW]

d = Average power consumption during peak drilling shift [MW]

$ERR_{(Reg)}$ = ERR determined with regression model [%]

T_{Est} = Estimated target for potential energy savings [%]

The tools developed in this section for quantifying potential energy savings are verified in Section 3.5. These tools and their functions are summarised in Table 16.

Table 16: Summary of new tools developed to quantify potential savings

TOOL	TOOL DESCRIPTION	TOOL FUNCTION
$b - [d - ((ERR_{(Pre)} + ERRI_{(MIn)}) \times d)] = T_{Min}$	Minimum expected benchmark savings	Estimate minimum potential energy savings
$b - [d - ((ERR_{(Pre)} + ERRI_{(Avg)}) \times d)] = T_{Avg}$	Average expected benchmark savings	Estimate average potential energy savings

TOOL	TOOL DESCRIPTION	TOOL FUNCTION
$b - [d - ((ERR_{(Pre)} + ERRI_{(Max)}) \times d)] = T_{Max}$	Maximum expected benchmark savings	Estimate maximum potential energy savings
$y = 0.7105x + 0.2439$	ERR regression model	Determine estimated post-implementation ERR with the regression model
$b - [d - (ERR_{(Reg)} \times d)] = T_{Est}$	Potential energy savings	**Quantify potential energy savings target**

Figure 37 summarises the methodology process required to quantify potential energy saving targets on compressed air systems. By considering the minimum, average and maximum expected savings, ESCOs are able to determine the viability of investigating potential energy saving projects. The regression model tool determines the projected savings target within the minimum, average and maximum expected saving ranges. This tool only require power consumption data (single-variable input) to quantify potential energy savings. The methodology process shown in Figure 37 can be discussed as follows:

2) With limited data, time and resources, the new practical tools can be used to quantify the potential savings on a compressed air system.

2.1) The pre-implementation ERR can be calculated with Equation 2 and the power consumption as an input.

2.2) With the pre-implementation ERR, the minimum, average and maximum expected energy saving ranges can be determined with Equations 3, 4 and 5. This enables ESCOs to determine the minimum or maximum potential return on investment with under- or overperformances.

2.3) The regression model (Equation 6) can be used to determine the projected post-implementation ERR.

2.4) By knowing the pre-implementation ERR and the expected energy saving ranges The post-implementation ERR obtained from the regression model can then be used to quantify the estimated saving target within these expected saving ranges by using Equation 7.

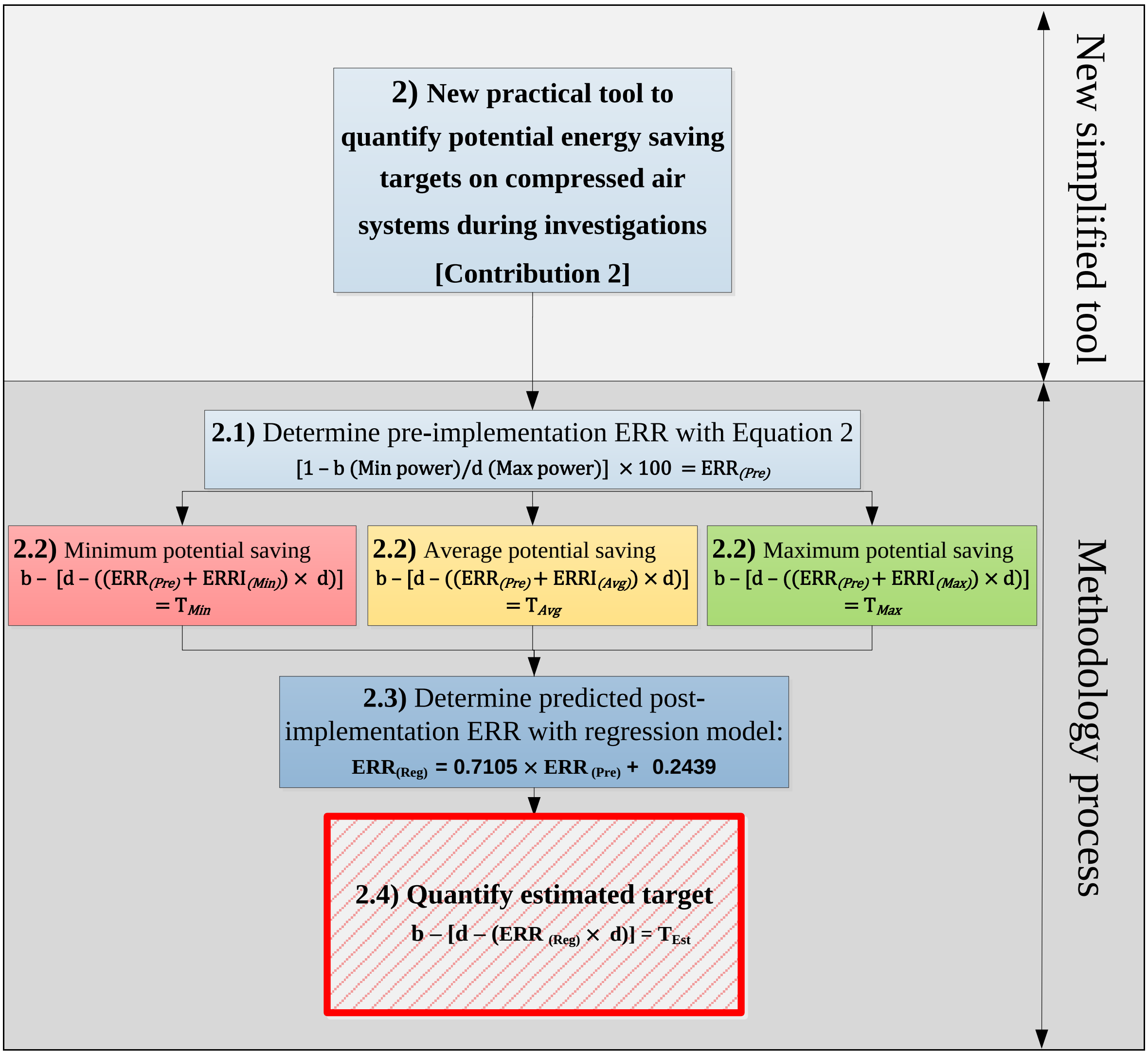


Figure 37: Methodology process for quantifying potential energy savings

3.4 A simplified high-level investigation methodology

Current economic conditions require ESCOs to take risks during the investigation phase of energy saving initiatives. Thus, it is not feasible for ESCOs to investigate all potential energy saving projects. The final step of this methodology chapter is combining the new simplified methods and tools developed in this chapter. This will enable ESCOs to conduct preliminary investigations to determine if specific energy saving projects would be worthwhile to invest the resources required to realise the available energy savings.

This new investigation methodology only requires power consumption data from a compressed air system. This single-variable input will enable ESCOs to investigate potential energy savings on deep-level mine compressed air systems with minimal risks and resources. If the specific project seems worthwhile based on the results of the new investigation methodology, then more detailed investigations including audits, simulations and integrated approaches with best-suited energy saving strategies can be considered.

The methodology for the new simplified high-level investigation is illustrated in Figure 38. It comprises of the required steps for implementing the new simplified methods and tools developed in this chapter. The simplified high-level investigation methodology can be explained as follows:

Contribution 1:	With limited data, time and resources, the new simplified benchmarking method can be used to rank compressed air systems according to scope for improvement.
Contribution 2:	Should insufficient data, time and resources be available for existing tools, the new practical tool can be used to quantify the potential savings of a compressed air system.
Contribution 3:	As a combination, the contributions of this study provide a single-variable high-level investigation methodology to investigate new potential energy saving projects with reduced resources and risks.

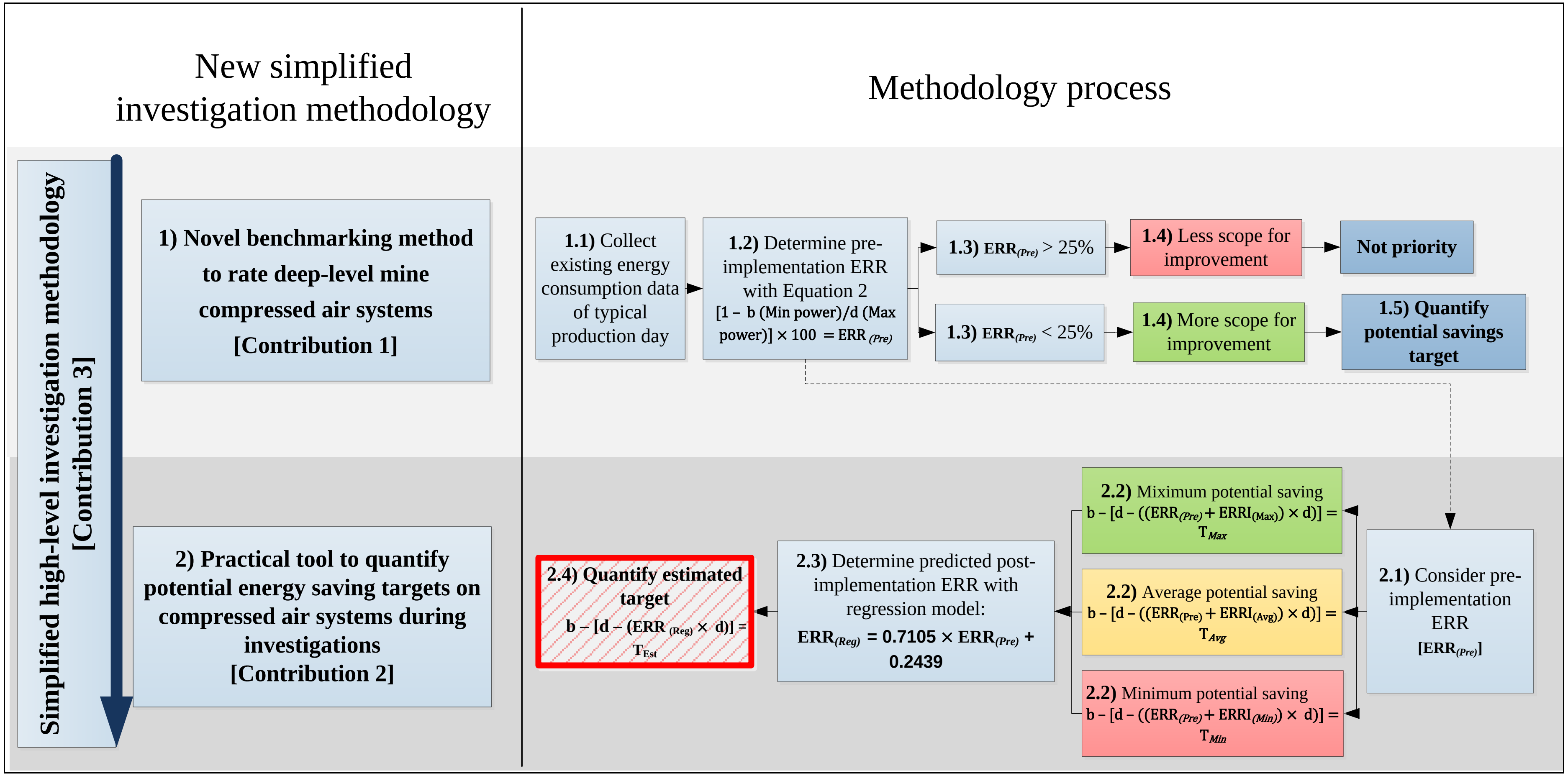


Figure 38: Simplified high-level investigation methodology process

3.5 Verification of new methods and tools

3.5.1 *Overview*

The contributions developed in this methodology chapter are verified in this section by comparing the new methods and tools with results from available methods and tools used in previous studies.

3.5.2 *Verify novel benchmarking method using simulation*

Overview

Contribution 1 is verified with a calibrated simulation in this section. This section discusses the verification through a simulation model develop for Mine C. A simplified compressed air layout of Mine C is shown in Figure 39. The compressed air system of Mine C has three main shafts. Shaft-C1 has two compressors located in the compressor house, Shaft-C2 has five compressors and Shaft-C3 only has two compressors. These compressors are connected to one compressed air network that supplies air to all three shafts.

During non-drilling shifts (14:00–07:00) of normal production days, Mine C operates Compressor-1 at Shaft-C1, Compressor-3 at Shaft-C2 and Compressor-8 at Shaft-C3. However, during the blasting shift, Mine C implements a load clipping initiative by stopping and starting Compressor-3. During the drilling shift, the mine additionally starts Compressor-7, Compressor-6 and Compressor-4 to accommodate the high-pressure demand.

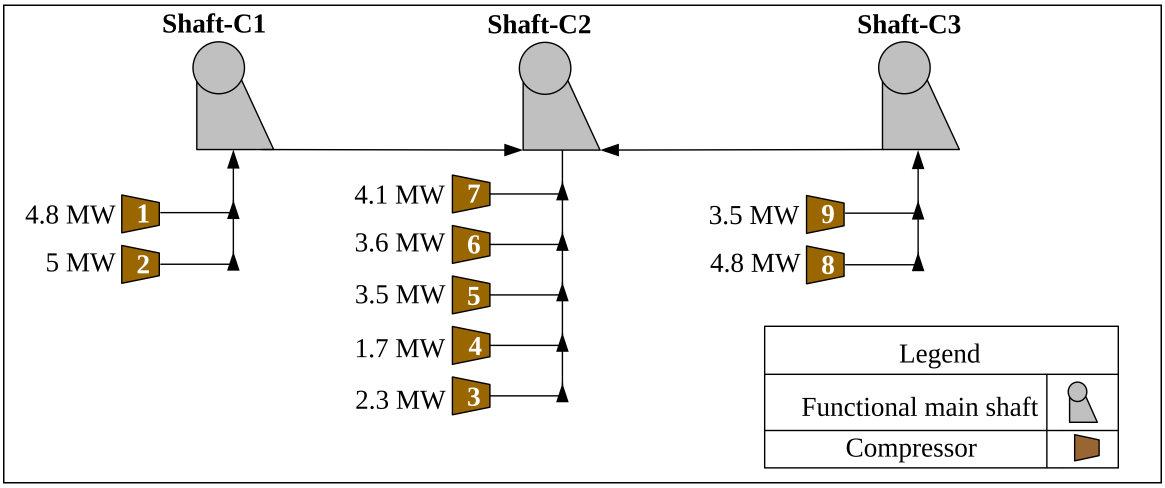


Figure 39: Compressed air layout of Mine C

Baseline power, flow and pressure data was collected for one month to develop and calibrate an accurate simulation model. The data acquisition took approximately 20 days to complete. An additional 12 days were required to develop the simulation model in Process Toolbox™. Therefore, the simulation model required an estimated 32 days to complete. Figure 64 in Appendix A shows the layout of the simulation model.

The header pressure and flow demand of a normal production day (not included in the baseline data) were inserted as multivariable data sets into the simulation model to determine the expected power consumption profile on a normal production day. Figure 40 compares this simulated power consumption profile with the actual power consumption profile of the same production day.

The simulation model was implemented to predict the power consumption by using actual flow and pressure data measured on a normal production day. The simulated result delivered an R^2 of 0.99 with an accuracy of 90% compared with the actual power data measured onsite. This indicates that the calibrated simulation developed with actual data was accurate and could be used to simulate different scenarios.

As seen from Figure 40, Mine C has implemented a load clipping initiative with a stop-and-start strategy by stopping Compressor-3 (2.3 MW) at Shaft-C2 during the peak blasting shift (16:00–20:00). However, Mine C confirmed that the stop-and-start strategy was not sustainable due to complaints of low header pressure on some levels underground, which still operate during blasting periods.

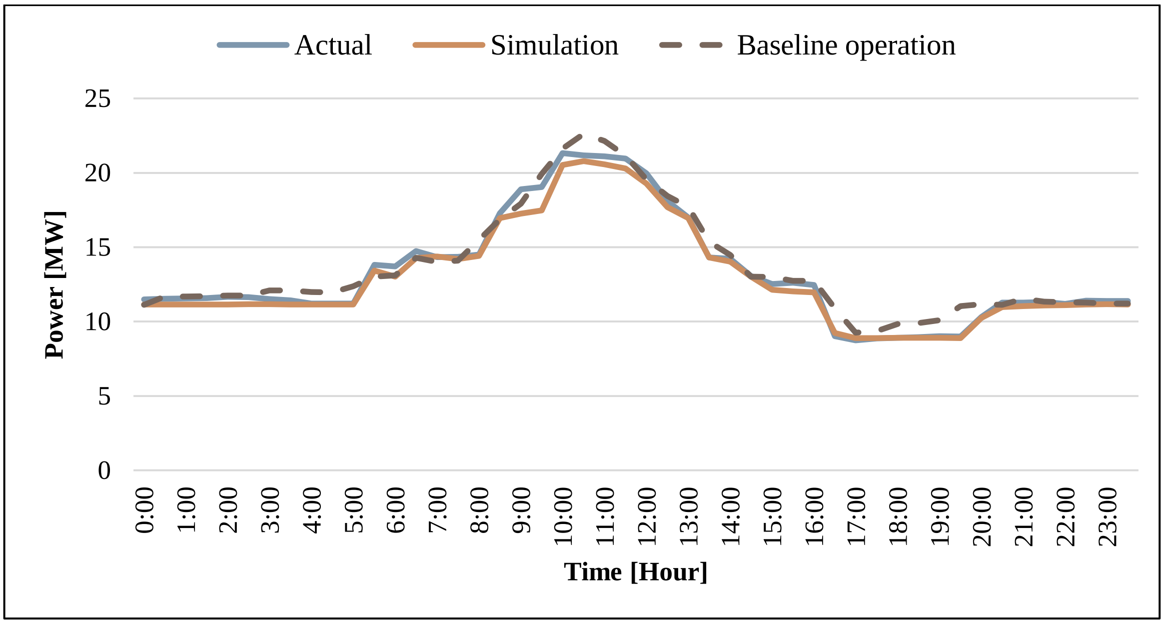


Figure 40: Normal production day power usage compared with simulated and baseline profiles

Simulating different scenarios

With the calibrated simulation available, two scenarios were simulated to verify the novel benchmarking method developed in Section 3.2. For Scenario 1 (see Figure 41), the header pressure during non-drilling shifts was reduced to the lowest potential pressure set point that allowed safe mining operations. According to mine personnel and simulation results, underground operations need approximately 250 kPa to supply compressed air all refuge bays (Best practise conditions).

Scenario 1 represents a best practice operation (see Figure 41). Should no compressor control be implemented, simulations indicated that Mine C would operate at a constant pressure of approximately 600 kPa throughout non-drilling shifts. The scenario was simulated as the poor practice operation (see Figure 41). The simulated and pressure and power consumption data is shown in Appendix A, Table 33 and Table 34.

The simulated scenarios in conjunction with the baseline operations allow for different compressed air system profiles that can be rated with the novel benchmarking method. If the results from the novel benchmark method correspond with the scenarios simulated with simulation model developed for Mine C, the novel benchmarking method is verified.

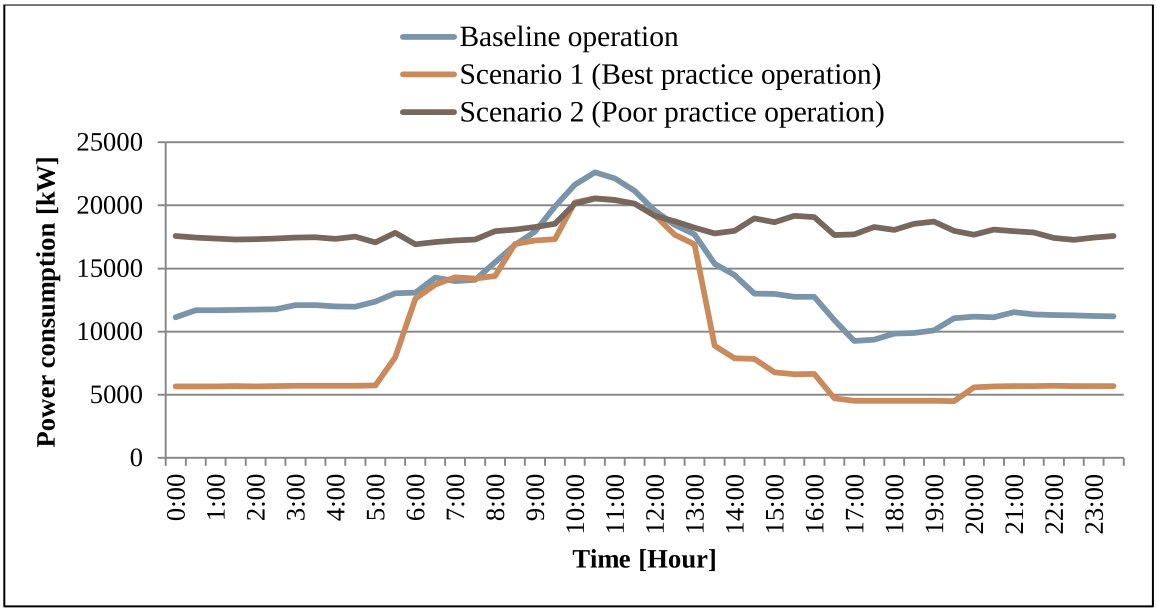


Figure 41: Simulated power usage of different scenarios compared with baseline operation

Expected results from the novel benchmarking method

This section compares the novel benchmarking method results with results from the calibrated simulation model. The novel benchmarking method only requires power consumption as a single-variable input to rank compressed air systems according to scope for improvement. The novel benchmarking method indicates that power consumption profiles with ERRs smaller than the benchmark average of 25% would have more scope for improvement than compressed air systems with ERRs larger than 25%.

Considering the baseline power demand profile and the simulated power consumption profiles of Scenario 1 and Scenario 2 illustrated in Figure 41, the expected result from the novel benchmarking method should indicate that Scenario 2 (poor practice) would have the most potential scope for improvement. Scenario 1 (best practice) should have the least scope for improvement, and the baseline power consumption should have the second-most scope for potential.

Results from the novel benchmarking method

The average power consumption for the baseline operation and different scenarios were calculated and summarised in Table 17. The novel benchmarking method ranked the compressed air profiles as indicated in Table 18. Scenario 2 had an ERR of 6% which is lower than the benchmark average. This scenario represented a poor practice operation. Thus, Scenario 2 was expected to have the most scope for improvement.

The second-ranked compressed air profile was the baseline operation. Although the baseline power profile ERR was above the average benchmark (53%), it was lower than Scenario 1 (best practice operation) which has an ERR of 76%. Thus, the baseline operation was ranked second and Scenario 1 last. This corresponded with the expected results from the simulation model (see Table 18). Therefore, the novel benchmarking method was verified with a calibrated simulation. The novel benchmarking method is verified further in Section 3.5.3 with an existing benchmarking method used in previous studies.

Table 17: Average drilling and blasting shift power consumption

INPUT DESCRIPTION	SYMBOL	BASELINE POWER [kW]	SCENARIO 1 POWER (BEST PRACTICE) [kW]	SCENARIO 2 POWER (POOR PRACTICE) [kW]
Average peak drilling shift power consumption	d	20425	19103	19494
Average peak blasting shift power consumption	b	10220	4506	18320

Table 18: Novel benchmarking method ranking compared to simulation results

Power consumption	ERR [%]	Ranking according to scope for improvement	
		Novel benchmark method result	Expected results from simulation
Baseline power consumption	53	2	2
Scenario 1 (Best practice)	76	3	3
Scenario 2 (Poor practice)	6	1	1

Verify novel benchmarking method with previous study

Overview

This section compares the novel benchmarking method with an existing benchmarking method previously used by Van der Zee in 2014 [33]. This will support the verification of Contribution 1. Figure 42 illustrates a process comparison between the available method developed and used by Van der Zee, and the new method developed in this study.

Van der Zee's study was identified to verify the novel benchmarking method due to the availability of the energy consumption profiles from his study. This available benchmarking method requires multivariable data sets to benchmark compressed air systems. These data sets include power consumption, production tonnes and mining depth. However, previous research indicated that production data is not readily accessible from all mines.

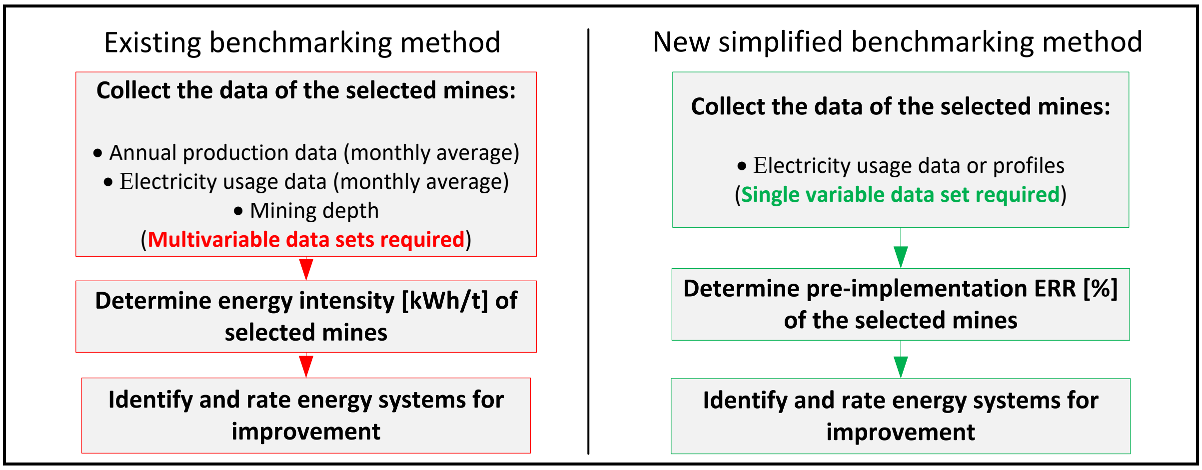


Figure 42: Existing benchmarking method process compared with simplified benchmarking method

Existing benchmarking method results

Among other mines used in Van der Zee's study, the energy intensity and mining depth data collected for Mine A and Mine H is shown in Figure 43. These mines were used due to the available power consumption profiles from Van der Zee's study [33]. Although the mining depths of Mine A and Mine H were similar, the energy intensity of Mine A (highlighted in red) was double the intensity of Mine H (highlighted in green). Based on the benchmarking method used by Van der Zee, Mine A had more scope for potential savings than Mine H.

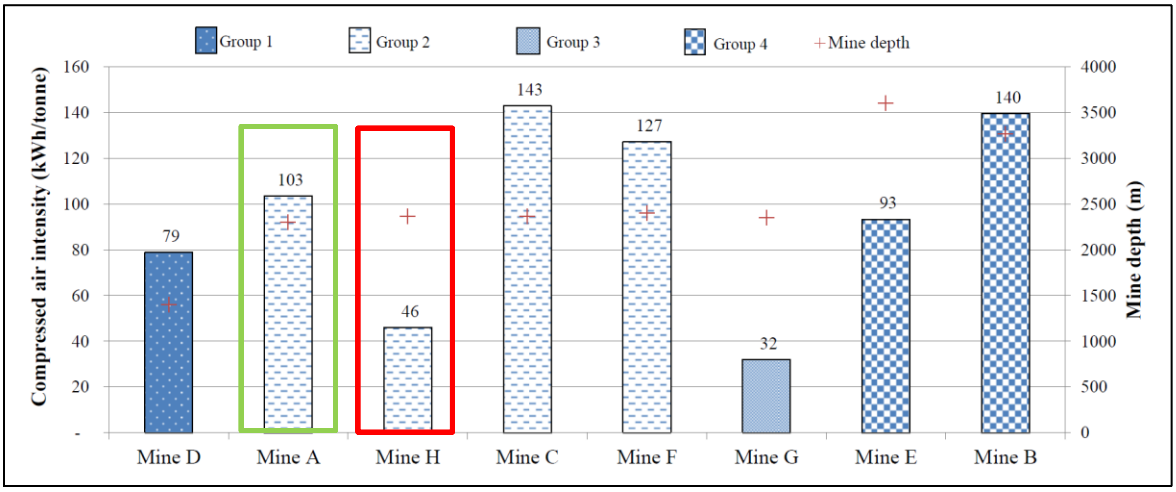


Figure 43: Energy intensity compared with mining depth of mines used

Novel benchmarking method results

In this section, the novel benchmarking method is implemented by considering the power consumption profiles available from Mine A and Mine H. The baseline power profile of Mine A is shown in Figure 44. The average power consumption during the peak drilling shift (d) is estimated to be 11 MW, and the average power consumption during the peak blasting shift is 11 MW (b). As a result, the pre-implementation ERR of Mine A is calculated to be 0%. Thus, the pre-implementation ERR of Mine A is below the average benchmark ERR of 25%.

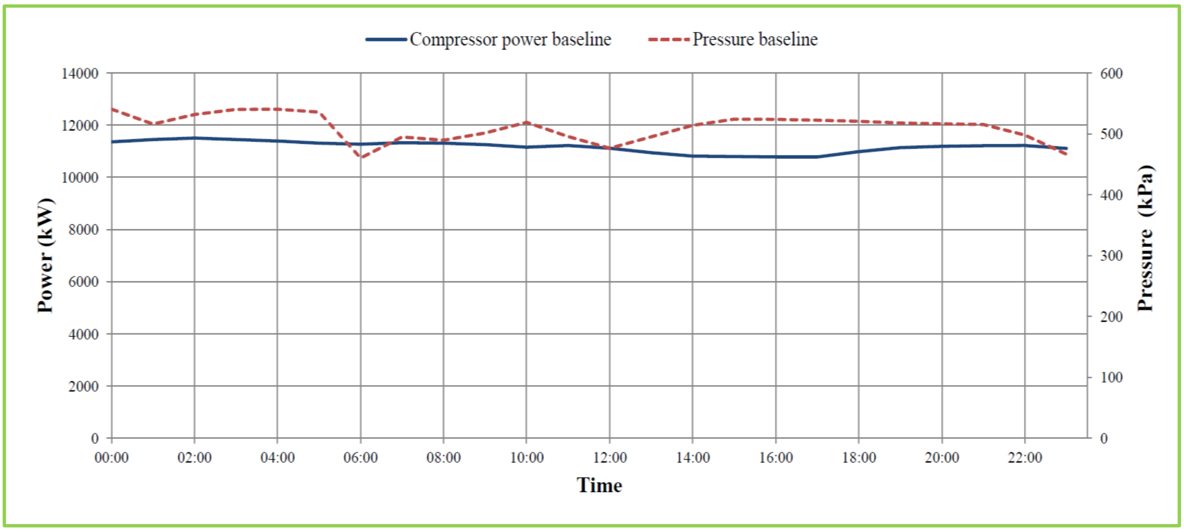


Figure 44: Power and pressure consumption profile of Mine A [33]

Mine H implemented an energy saving initiative that improved the baseline power consumption profile, which is indicated in Figure 45. However, to compare the available scope for improvement with Mine A before any energy saving initiatives were implemented on Mine H, the baseline power use profile was considered when ranking the mines according to scope for improvement.

The average power consumption of the baseline profile during peak drilling shift (d) was estimated to be 12 MW with an average power consumption during peak blasting shift of 8.4 MW (b). As a result, the pre-implementation ERR of the baseline profile was calculated to be 30%. Thus, the pre-implementation ERR of Mine H was above the average benchmark ERR of 25%. Therefore, Mine A had more scope for improvement than Mine H.

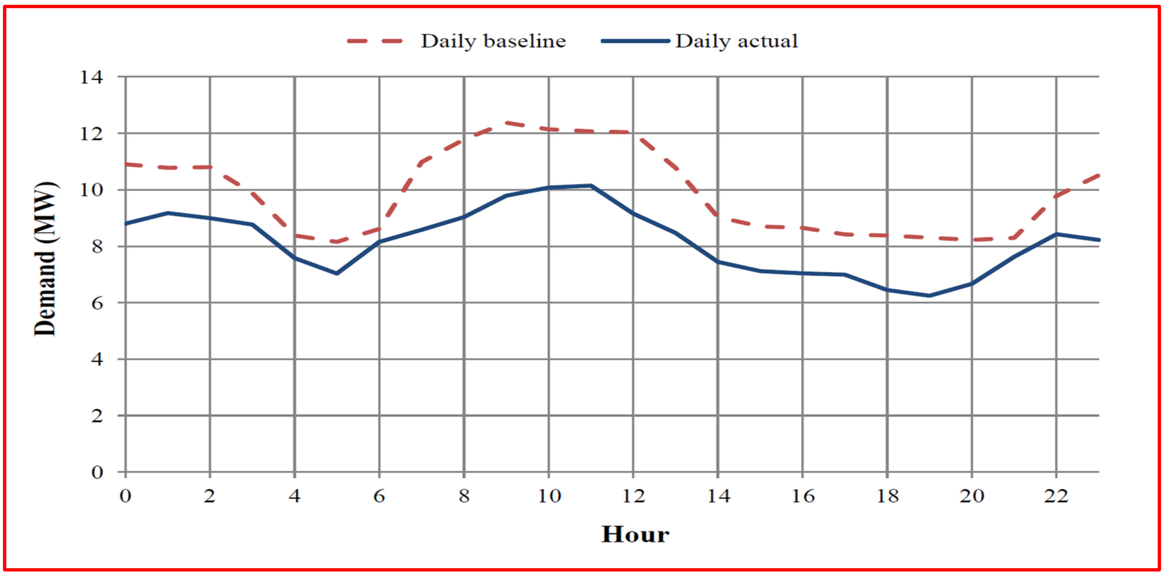


Figure 45: Baseline actual energy consumption profile on Mine H [33]

Available and new benchmarking method comparison

Table 19 compares the results from the existing benchmarking method with the results of the new simplified benchmarking method. Both methods indicate that the Mine A has more potential for energy savings. However, the new simplified method only requires power consumption profiles to benchmark the compressed air systems. The existing benchmarking method required production data and mining depth, which are not always readily accessible.

Table 19: Existing and new simplified methods result in comparison

BENCHMARKING METHOD	MINE WITH MORE SCOPE FOR IMPROVEMENT	MINE WITH LESS SCOPE FOR IMPROVEMENT
Existing method	Mine A	Mine H
New simplified method	Mine A	Mine H

Value of novel benchmarking method

As previously stated in Chapter 2, obtaining multivariable data sets could prolong investigation periods. Therefore, by using only power consumption as a single-variable input, the resources and risks required to benchmark compressed air systems during investigation could be reduced.

Therefore, the new benchmarking method enables ESCOs to rank compressed air systems according to scope for improvement with limited resources and minimal risks.

3.5.3 *Verify practical tool with existing simplified tool*

Overview

In this section, the new practical tool developed in Section 3.3 is compared with an existing simplified tool used to quantify potential energy savings in a previous study conducted by Marais in 2012 [17]. This previous study will be referred to as the DSM project 1, which was discussed in Section 2.7.2. This study was selected due to the data availability from the study.

The existing simplified tool process is compared with the new practical tool for quantifying potential energy savings in Figure 46. Both tools are expected to estimate potential savings targets with minimum input. However, the new practical tool only requires power consumption as an input compared with the existing simplified tool that needs both pressure and power data sets.

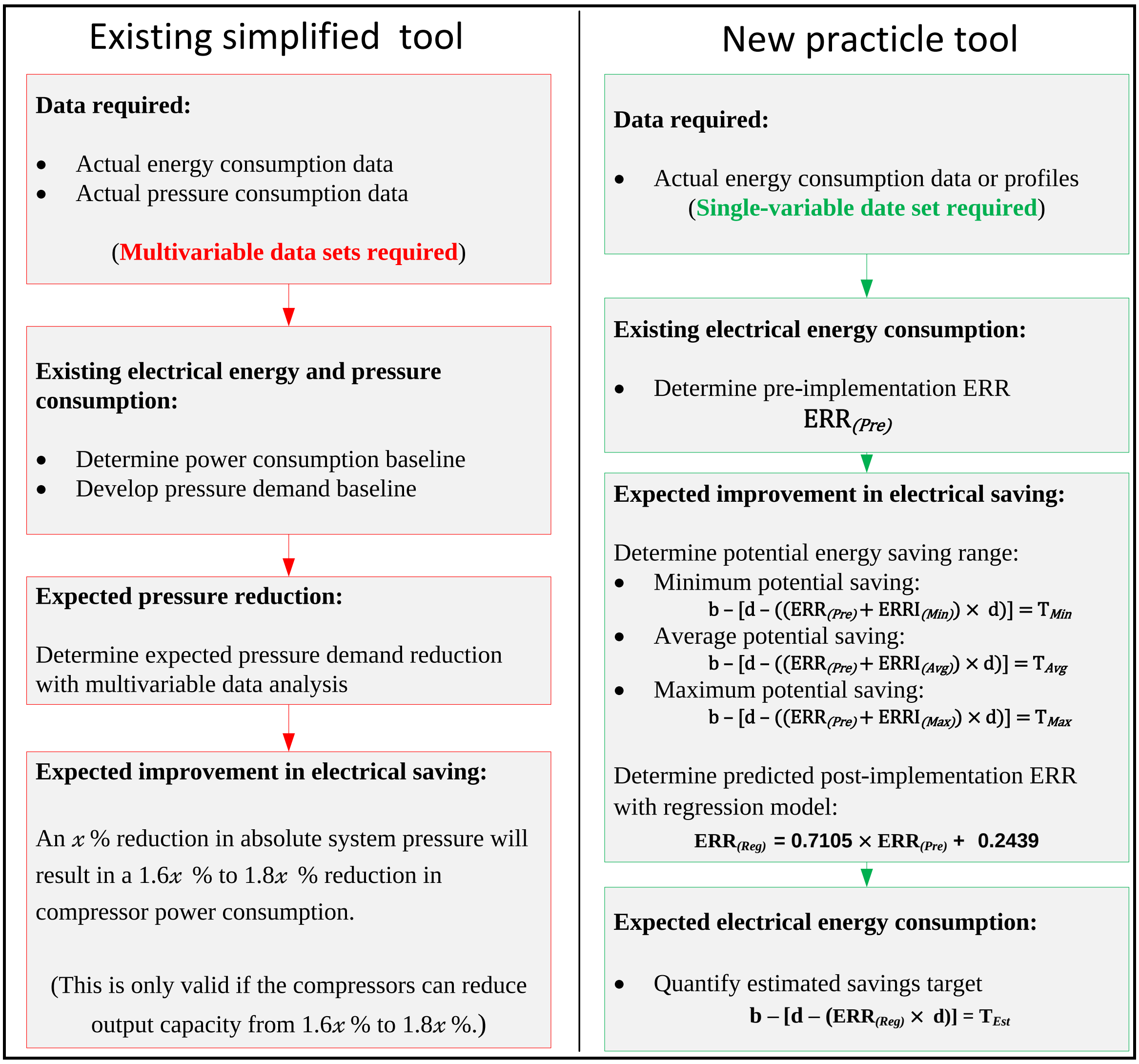


Figure 46: Existing simplified tool process compared with the novel simplified tool

Existing simplified tool used in DSM project 1

DSM project 1 evaluated the impact of an integrated approach which was developed by Marais in 2012 and was previously discussed in Section 2.7.2. Marais implemented the integrated approach on a compressed air system with available power and pressure demand data sets. A simplified tool was developed by Marais in 2012 to enable ESCOs and mines to determine potential energy savings with pressure and power consumption profiles. However, this tool is limited to a pressure range between 300 kPa and 700 kPa, and Marais found that these pressure profiles were not always readily available.

The available pressure and power demand profiles from DSM project 1 are used in this section to verify the new practical tool with existing simplified tool develop by Marais. In DSM project 1 (Section 2.7.2), Marais implemented his simplified tool to quantify total potential savings impact throughout the day. However, to verify the new practical tool, Marais's simplified tool will be implemented again on the same profiles, but this time to only focus on quantifying the potential savings during Eskom's evening peak period. The same profiles are also used with the new practical tool. The results are then compared with the actual savings achieved by reducing the set points on the specific compressed air system.

After detailed investigations and discussions, mine personnel from DSM project 1 approved a compressor delivery pressure of 550 kPa for drilling periods, and 490 kPa for non-drilling periods. This decision was based on experience that these pressures would be sufficient to counter the pressure drop due to line friction. Thus, mining operations should continue to operate without limits when the pressure is reduced. Figure 47 compares the baseline system pressure with the proposed system pressure.

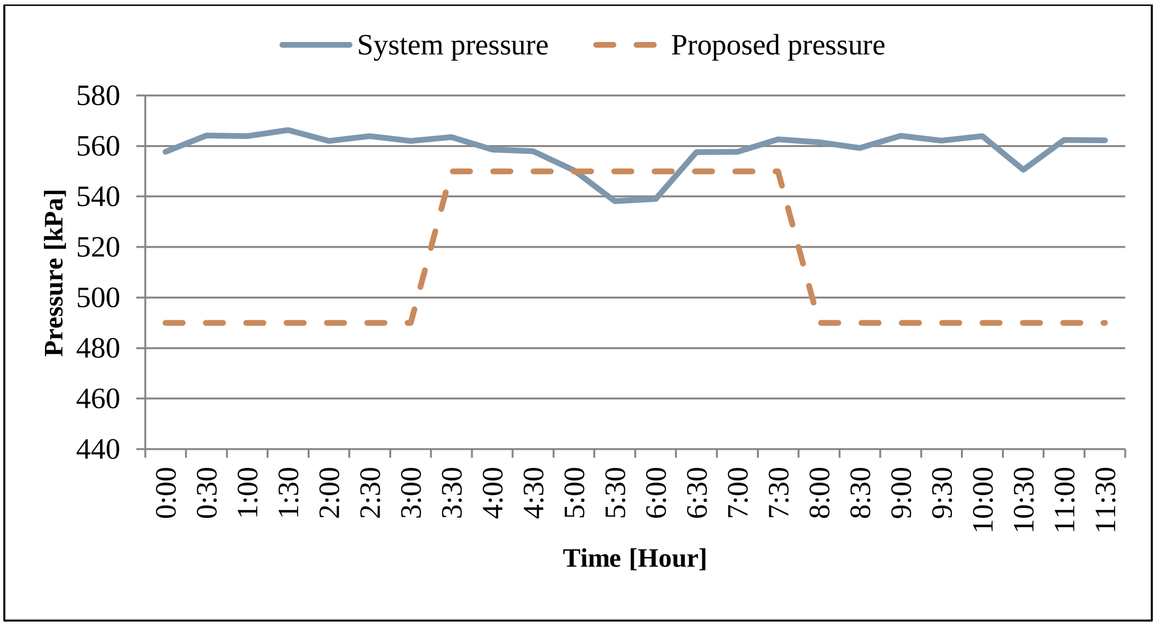


Figure 47: Existing system pressure compared with proposed system pressure [17]

Results from existing simplified tool

The impact of the proposed pressure set points in Figure 47 was simulated with the existing simplified tool developed by Marais. Figure 48 compares the simulated result from the existing simplified tool with the baseline. The impact estimated with the existing simplified tool during Eskom evening peak period is expected to be 1.44 MW. However, the actual impact shown in Figure 48 realised a saving of 2 MW. Thus, the expected power saving from the existing simplified tool was accurate within 28% of the actual impact during the Eskom evening period.

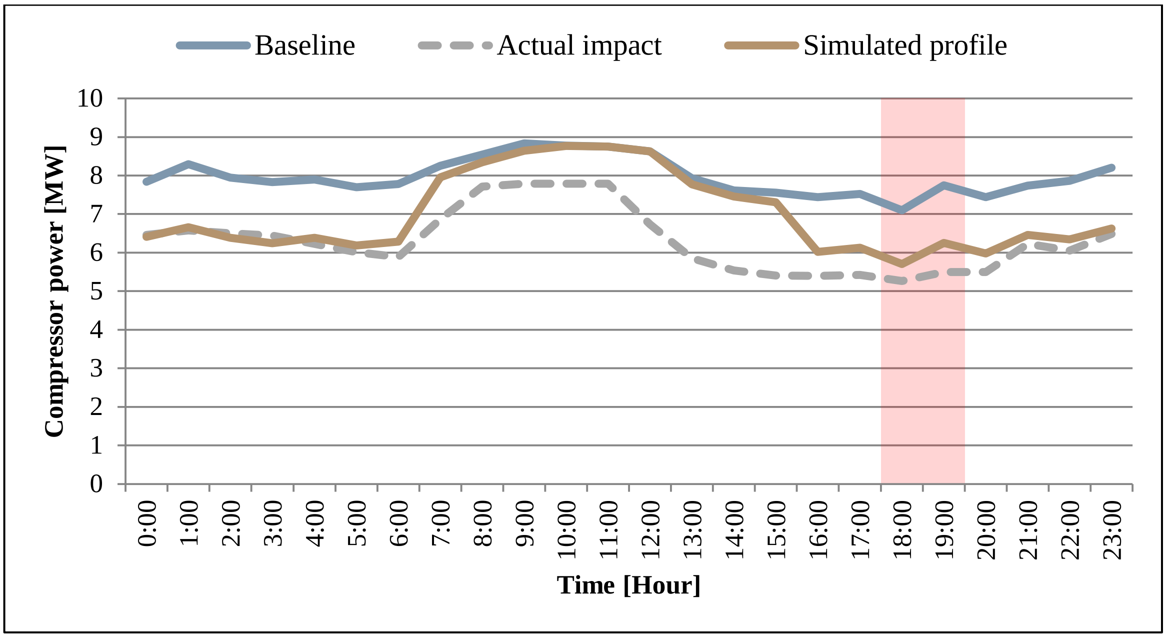


Figure 48: Simulated energy consumption compared with baseline power consumption [17]

Results from new practical tool

The new simplified tool can be used by determining the pre-implementation ERR from the baseline power consumption profile shown in Figure 48. Therefore, it was determined that the pre-implementation ERR for this verification study was 14%. A calculator was developed in Microsoft Excel™ for calculating the potential improvements using the novel simplified tool methodology previously shown in Figure 37. This calculator only requires the average power consumption during the peak drilling (d) and peak blasting shift (b) as input. The input field is shown in Table 20 and the results are shown in Table 21.

Table 20: Inputs required for novel simplified tool calculator

INPUT DESCRIPTION	SYMBOL	POWER [MW]
Average peak drilling shift power consumption	d	8.75
Average peak blasting shift power consumption	b	7.42

The results shown in Table 21 indicate that the expected benchmark minimum saving was 0.5 MW, the average benchmark 1.5 MW, and the maximum potential energy saving 2.8 MW. By implementing the regression model, the expected post-implementation ERR was expected to be 35%. This would result in a predicted saving of 1.75 MW. Thus, the actual saving was expected to be within the range of the average expected benchmark saving and maximum expected benchmark saving range.

Table 21: Potential improvement quantified with novel simplified tools in Verification study 1

DESCRIPTION	ERR INCREASE [%]	ESTIMATED POWER USAGE [MW]	ESTIMATED SAVING [MW]	ACCURACY TO ACTUAL SAVING [%]
Pre-implementation ERR	15	–	–	–
Regression model ERR	35	5.7	**1.75**	87
Benchmark minimum ERR increase	12	6.9	0.5	13
Benchmark average ERR increase	32	5.9	1.5	75
Benchmark maximum ERR increase	47	4.6	2.8	41

New tool result compared to existing tool

Considering the results shown in Figure 48, the actual saving was within the expected ranges estimated with the new practical calculator. The regression model saving prediction was calculated to be accurate within 13% of the actual saving of 2 MW. This was 15% more accurate than the existing simplified tool used in the case study from the previous research conducted by Marais (see Table 22) [17].

Table 22: New tool result compared to existing tool

METHOD	PREDICTED SAVING [MW]	ACCURACY TO ACTUAL SAVING [%]
New tool	1.75	87
Existing tool	1.44	72
Actual saving	2	-

3.5.4 Verify practical tool with existing simplified tool used on other studies

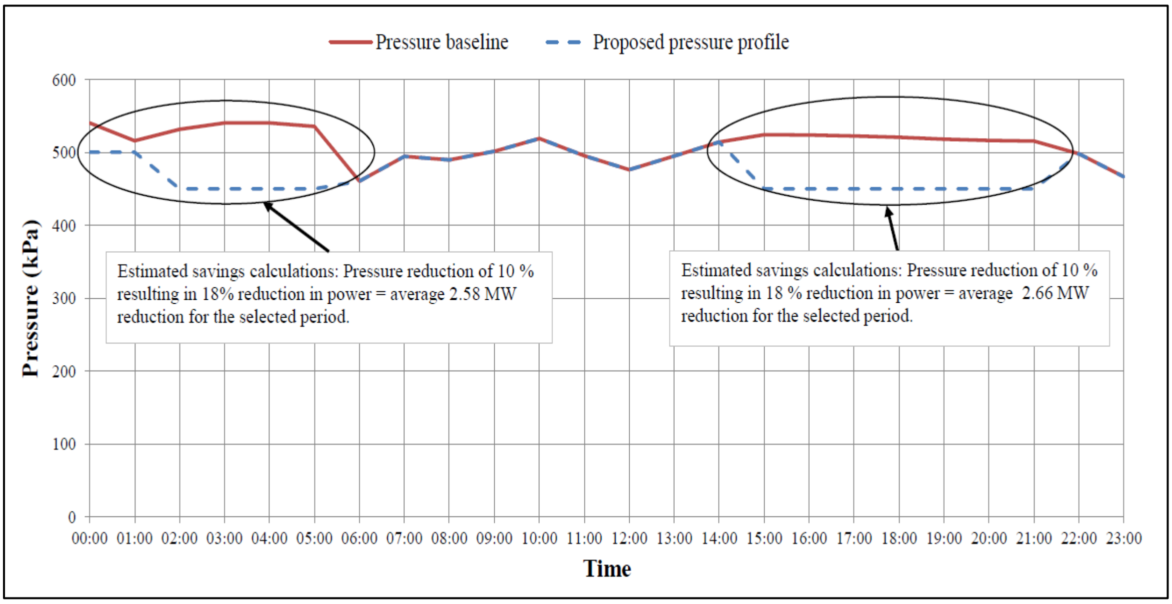
Overview

The existing simplified tool develop by Marais in 2012 was used in another study conducted by Van der Zee in 2014 on Mine A, which was previously discussed in Section 3.5.3 to verify the novel benchmarking method. This section compares the results achieved by Van der Zee and the new practical tool developed in this study by using the same data sets as inputs. This specific study of Van der Zee was selected to compare the new practical tool due to the data availability.

Existing simplified tool result

Van der Zee used this existing simplified tool due to the limited information that was available from the compressed air system on Mine A. Figure 49 shows the estimated savings found by Van der Zee with the existing simplified tool that required pressure and power consumption profiles.

Van der Zee determined that the pressure during non-drilling shifts could be reduced by 10%. As a result, the average estimated saving during the non-drilling shift, including the Eskom evening peak period, was 2.66 MW.



Estimated savings calculations: Pressure reduction of 10 % resulting in 18% reduction in power = average 2.58 MW reduction for the selected period.

Estimated savings calculations: Pressure reduction of 10 % resulting in 18 % reduction in power = average 2.66 MW reduction for the selected period.

Figure 49: Pressure baseline and proposed pressure profile of Mine A

New practical tool result

The new practical tool estimated a minimum saving of 0.66 MW, an average of 1.87 MW, and a maximum potential energy saving of 3.52 MW. By implementing the regression model, the expected post-implementation ERR was expected to be 24%. This would result in a predicted saving of 2.68 MW during the Eskom evening peak period.

This correlates with the average expected energy saving (2.66 MW) from the existing simplified tool used by Van der Zee on Mine A (see Table 23). Thus, compared with an existing simplified tool, the new practical tool has been verified as a tool that can be used to quantify potential energy savings during Eskom evening peak periods. However, the new simplified tool only requires power consumption as a single-variable input to quantify potential savings. This will reduce the input and risk required from ESCOs to estimate potential savings target during investigation of new energy saving projects.

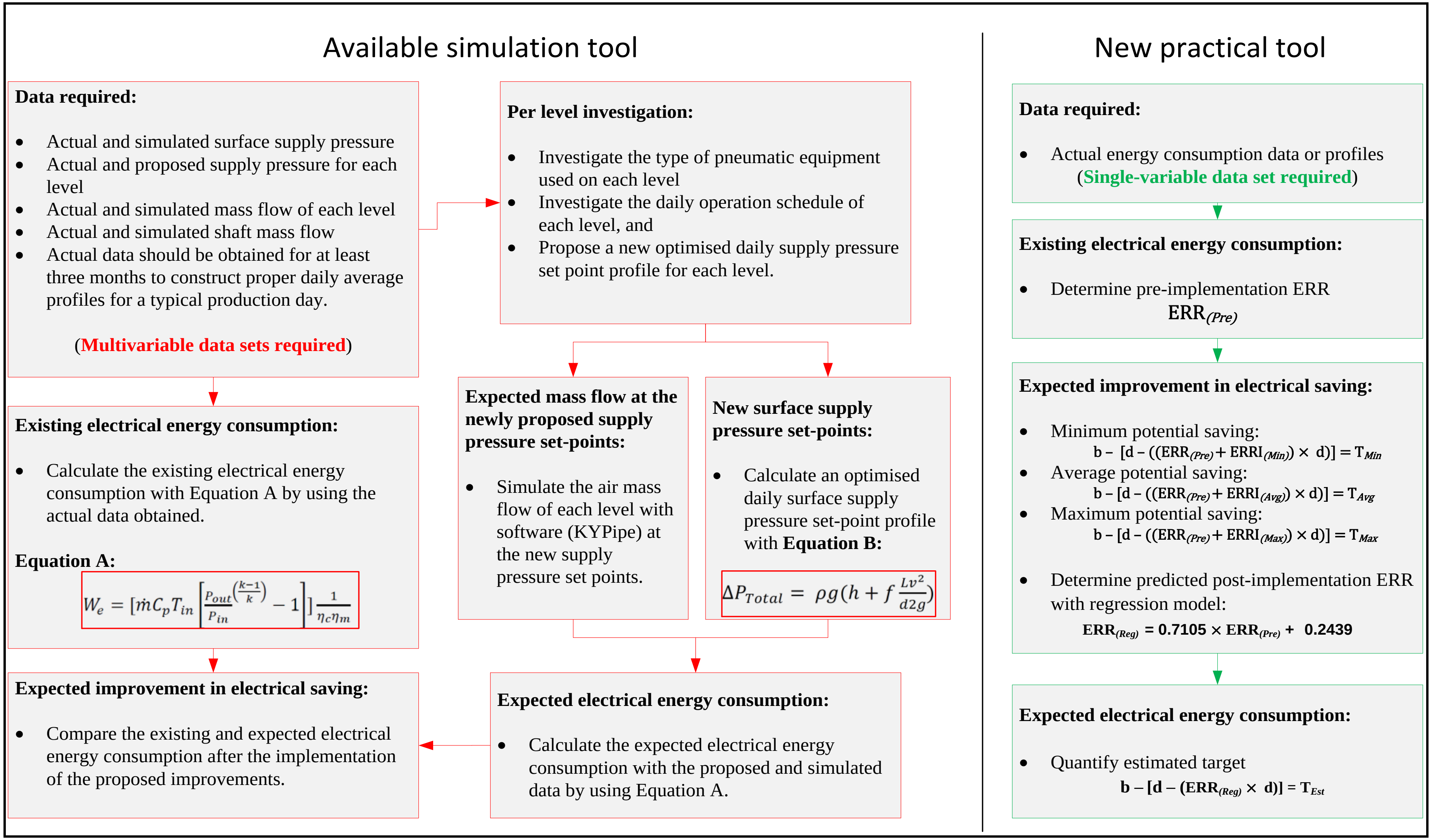
Table 23: New tool result compared to existing tool

METHOD	PREDICTED SAVING [MW]
New	2.68
Existing	2.66
Actual saving	Simulated with tools (no actual implementation conducted)

3.5.5 *Verify practical tool with complex simulation tool used in a previous study*

Overview

In this section, the new simplified tool is compared with a complex simulation tool used in a previous study also conducted by Marais in 2012 [17]. The new simplified tool process is compared with an available simulation process in Figure 50. The simulation process requires multivariable data sets to develop the simulation model. As previously discussed, these variables are not always readily accessible. The practical tool only requires power consumption as a single variable input.



Available simulation tool

Data required:

- Actual and simulated surface supply pressure
- Actual and proposed supply pressure for each level
- Actual and simulated mass flow of each level
- Actual and simulated shaft mass flow
- Actual data should be obtained for at least three months to construct proper daily average profiles for a typical production day.

(**Multivariable data sets required**)

Per level investigation:

- Investigate the type of pneumatic equipment used on each level
- Investigate the daily operation schedule of each level, and
- Propose a new optimised daily supply pressure set point profile for each level.

Existing electrical energy consumption:

- Calculate the existing electrical energy consumption with Equation A by using the actual data obtained.

Equation A:

$$W_e = \left[\dot{m} C_p T_{in} \left[\frac{P_{out}}{P_{in}}^{\left(\frac{k-1}{k}\right)} - 1 \right]\right] \frac{1}{\eta_c \eta_m}$$

Expected mass flow at the newly proposed supply pressure set-points:

- Simulate the air mass flow of each level with software (KYPipe) at the new supply pressure set points.

New surface supply pressure set-points:

- Calculate an optimised daily surface supply pressure set-point profile with **Equation B:**

$$\Delta P_{Total} = \rho g \left(h + f \frac{Lv^2}{d2g}\right)$$

Expected improvement in electrical saving:

- Compare the existing and expected electrical energy consumption after the implementation of the proposed improvements.

Expected electrical energy consumption:

- Calculate the expected electrical energy consumption with the proposed and simulated data by using Equation A.

New practical tool

Data required:

- Actual energy consumption data or profiles (**Single-variable data set required**)

Existing electrical energy consumption:

- Determine pre-implementation ERR $\mathrm{ERR}_{(Pre)}$

Expected improvement in electrical saving:

- Minimum potential saving:
  $b - [d - ((\mathrm{ERR}_{(Pre)} + \mathrm{ERRI}_{(Min)}) \times d)] = T_{Min}$
- Average potential saving:
  $b - [d - ((\mathrm{ERR}_{(Pre)} + \mathrm{ERRI}_{(Avg)}) \times d)] = T_{Avg}$
- Maximum potential saving:
  $b - [d - ((\mathrm{ERR}_{(Pre)} + \mathrm{ERRI}_{(Max)}) \times d)] = T_{Max}$
- Determine predicted post-implementation ERR with regression model:
  $\mathrm{ERR}_{(Reg)} = 0.7105 \times \mathrm{ERR}_{(Pre)} + 0.2439$

Expected electrical energy consumption:

- Quantify estimated target
  $b - [d - (\mathrm{ERR}_{(Reg)} \times d)] = T_{Est}$

Figure 50: Available simulation tool process compared with new practical tool

The detailed simulation process was implemented on a study from previous research to quantify potential energy savings. The compressed air system included in this study consisted of eight compressors with a total operational capacity of 36 MW. These compressors supply air to several end users on the surface, which includes three main shafts leading to underground operations.

This previous study was used to compare the complex simulation and new practical tool due to the data availability. Figure 51 shows the power and pressure demand profiles of this study.

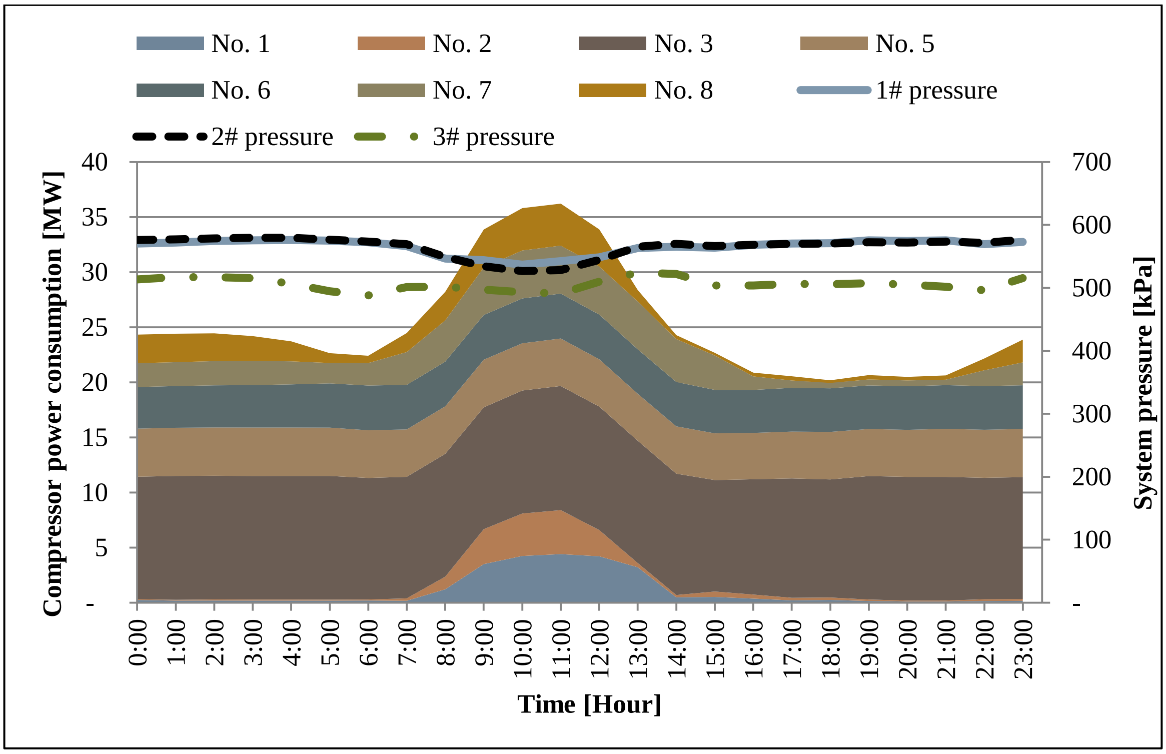


Figure 51: Baseline profiles used as inputs in a study with available simulation tools [17]

Result achieved with complex simulation

The first step for this study was implementing improved compressor control. A detail simulation was conducted to predict the impact of the new compressor control. The simulation estimated that a saving of 2.2 MW could be achieved. The second step for this study was optimising the compressor combination with the improved compressor controls. After implementing the second step, the detailed simulation model indicated that the potential savings could increase to an estimated 5 MW. Actual tests were conducted, and as a result, an actual impact of 4.5 MW was achieved [17]. Thus, the simulation in this study was accurate within 10%.

Result achieved with the new practical tool

The new simplified tool can be used by determining the pre-implementation ERR with the readily accessible power consumption data. The average power consumption for this study during peak drilling (d) was 32.9 MW and 20 MW during peak blasting (b). As a result, the pre-implementation ERR was calculated as 39%. Table 24 shows the savings quantified with the new simplified tool.

The results from in Table 24 show that the estimated minimum saving is expected to be 2 MW, the average 5.6 MW, and the maximum potential energy saving 10.5 MW. By implementing the regression model, the predicted post-implementation ERR is expected to be 52%. This leads to a foreseen saving of 4.29 MW. Thus, the actual saving is expected to be within the range of the average expected benchmark saving and minimum expected benchmark saving.

Table 24: Potential improvement quantified with novel simplified tool

DESCRIPTION	ERR INCREASE [%]	ESTIMATED POWER USAGE [MW]	ESTIMATED SAVING [MW]	ACCURACY TO ACTUAL SAVING [%]
Pre-implementation ERR	39	–	–	–
Regression model ERR	52	15.7	**4.29**	95
Benchmark minimum ERR increase	45	18.0	2.0	45
Benchmark average ERR increase	56	14.2	5.6	75
Benchmark maximum ERR increase	71	9.4	10.5	135

New tool result compared to existing tool

The actual saving target within the expected ranges was estimated with the new simplified tool. The estimated saving from the regression model was accurate within 5% of the actual saving of 4.5 MW. This is 5% more accurate than the simulation tool used by Marais (see Table 25). The results, therefore, indicated that the simplified tool could be used to quantify potential energy savings by only requiring power consumption as a single-variable input.

Table 25: New tool result compared to existing tool

METHOD	PREDICTED SAVING [MW]	ACCURACY TO ACTUAL SAVING [%]
New tool	4.29	95
Existing tool	5	90
Actual saving	4.50	-

3.5.6 Verification of a simplified high-level investigation methodology

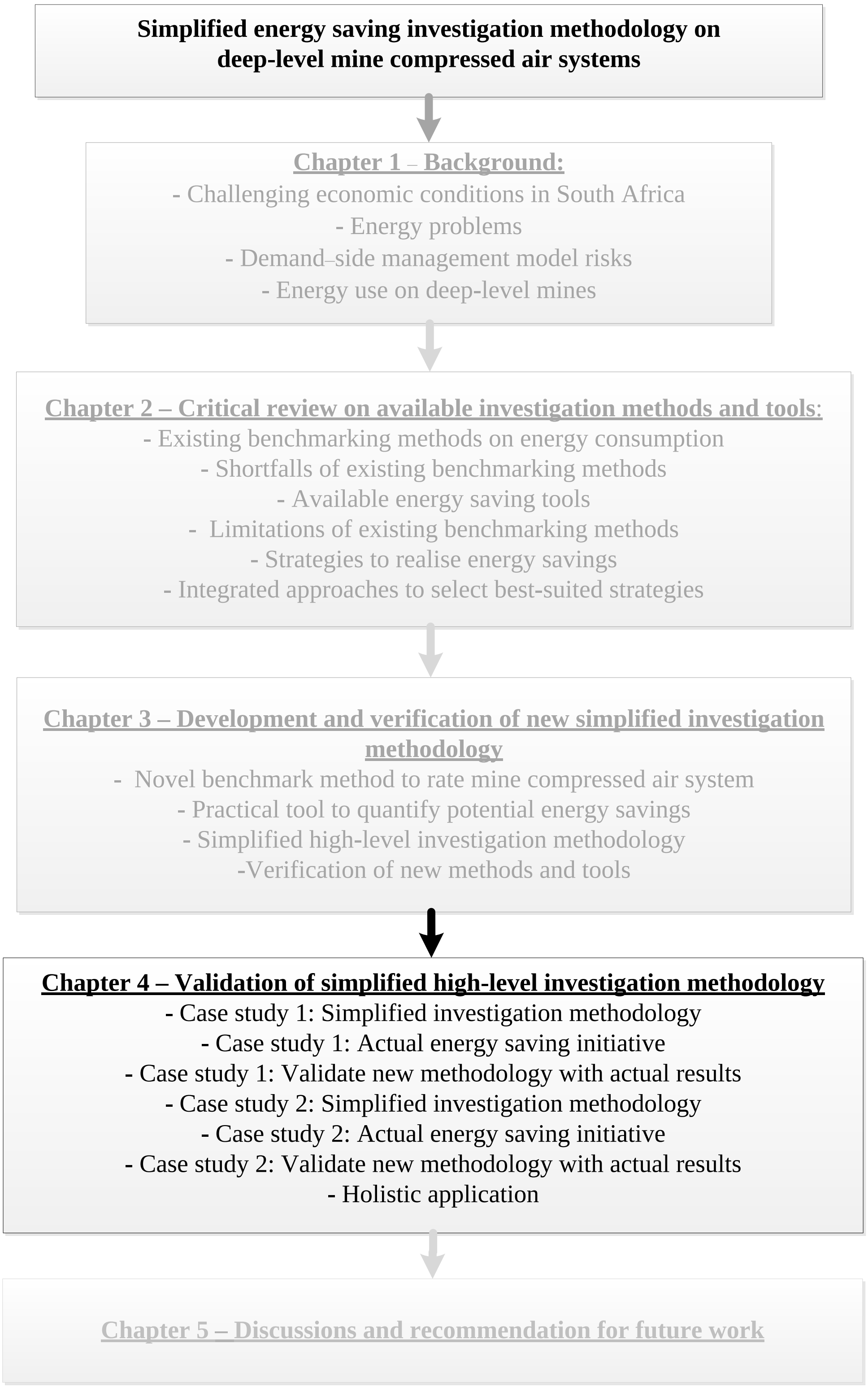
Contribution 3 can be considered verified with the combined verification results obtained from Contribution 1 and Contribution 2. However, the simplified high-level investigation methodology is validated and verified further in Chapter 5 using actual case studies.

3.6 **Conclusion**

In this methodology chapter, new simplified methods and tools were developed to rank compressed air systems according to scope for improvement and to quantify potential savings awarded during Eskom's evening peak period. Existing methods and tools used during investigation processes require multivariable data sets. The new simplified methods and tools were developed to only use power consumption as a single-variable input.

The existing and new methods were compared by using the same data sets as inputs for verification. The results were sufficiently accurate and could be achieved with limited time and resources. Therefore, these new methods and tools can be integrated as a simplified high-level investigation methodology to enable ESCOs to investigate more potential energy saving projects. Chapter 4 further verifies the new developed solutions and validates the methodology by implementing the new high-level investigation methodology on actual case studies.

4 VALIDATION OF SIMPLIFIED HIGH-LEVEL INVESTIGATION METHODOLOGY



Simplified energy saving investigation methodology on deep-level mine compressed air systems

Chapter 1 – Background:
- Challenging economic conditions in South Africa
- Energy problems
- Demand–side management model risks
- Energy use on deep-level mines

Chapter 2 – Critical review on available investigation methods and tools:
- Existing benchmarking methods on energy consumption
- Shortfalls of existing benchmarking methods
- Available energy saving tools
- Limitations of existing benchmarking methods
- Strategies to realise energy savings
- Integrated approaches to select best-suited strategies

Chapter 3 – Development and verification of new simplified investigation methodology
- Novel benchmark method to rate mine compressed air system
- Practical tool to quantify potential energy savings
- Simplified high-level investigation methodology
-Verification of new methods and tools

Chapter 4 – Validation of simplified high-level investigation methodology
- Case study 1: Simplified investigation methodology
- Case study 1: Actual energy saving initiative
- Case study 1: Validate new methodology with actual results
- Case study 2: Simplified investigation methodology
- Case study 2: Actual energy saving initiative
- Case study 2: Validate new methodology with actual results
- Holistic application

Chapter 5 – Discussions and recommendation for future work

4.1 Preamble

This section combines and implements the new simplified methods and tools developed in Chapter 3 as a simplified high-level investigation methodology. The investigation methodology is validated through case studies on actual deep-level mine compressed air systems. The validation process will be done as follows:

1. **Implement new simplified high-level investigation methodology on case studies:**
    1.1 Rank mines according to scope for improvement with the novel benchmarking method.
    1.2 Quantify potential energy saving targets with new practical tool.
2. **Evaluate actual results of energy saving initiatives**
    2.1 Establish baseline power consumption of compressed air systems.
    2.2 Implement energy saving initiatives.
    2.3 Determine actual impact of energy saving initiatives.
3. **Validate new simplified high-level investigation methodology with results:**
    3.1 Validate the novel benchmarking method for ranking compressed air systems according to potential scope for improvement (Contribution 1).
    3.2 Validate the practical tool for quantifying savings (Contribution 2).
    3.3 Validate the new simplified high-level investigation methodology (Contribution 3).

The projects implemented in these case studies were IDM-funded projects that rewarded energy savings during Eskom's evening peak periods. Independent M&V teams appointed by Eskom verified the data. Thus, an assumption is made that the quality of the data sets used for these case studies is according to ISO 50001 standard.

4.2 Implement the simplified investigation methodology on Case Study 1

4.2.1 Overview

For Case Study 1, the new investigation methodology was systematically implemented according to the steps discussed in the methodology process previously shown in Figure 38. Figure 52 illustrates the compressed air system layout used in Case Study 1.

Five compressors pressurised this compressed air system with a combined installed capacity of 22.5 MW. These compressors supplied air to two active main shafts, one smelter plant and one concentrator plant.

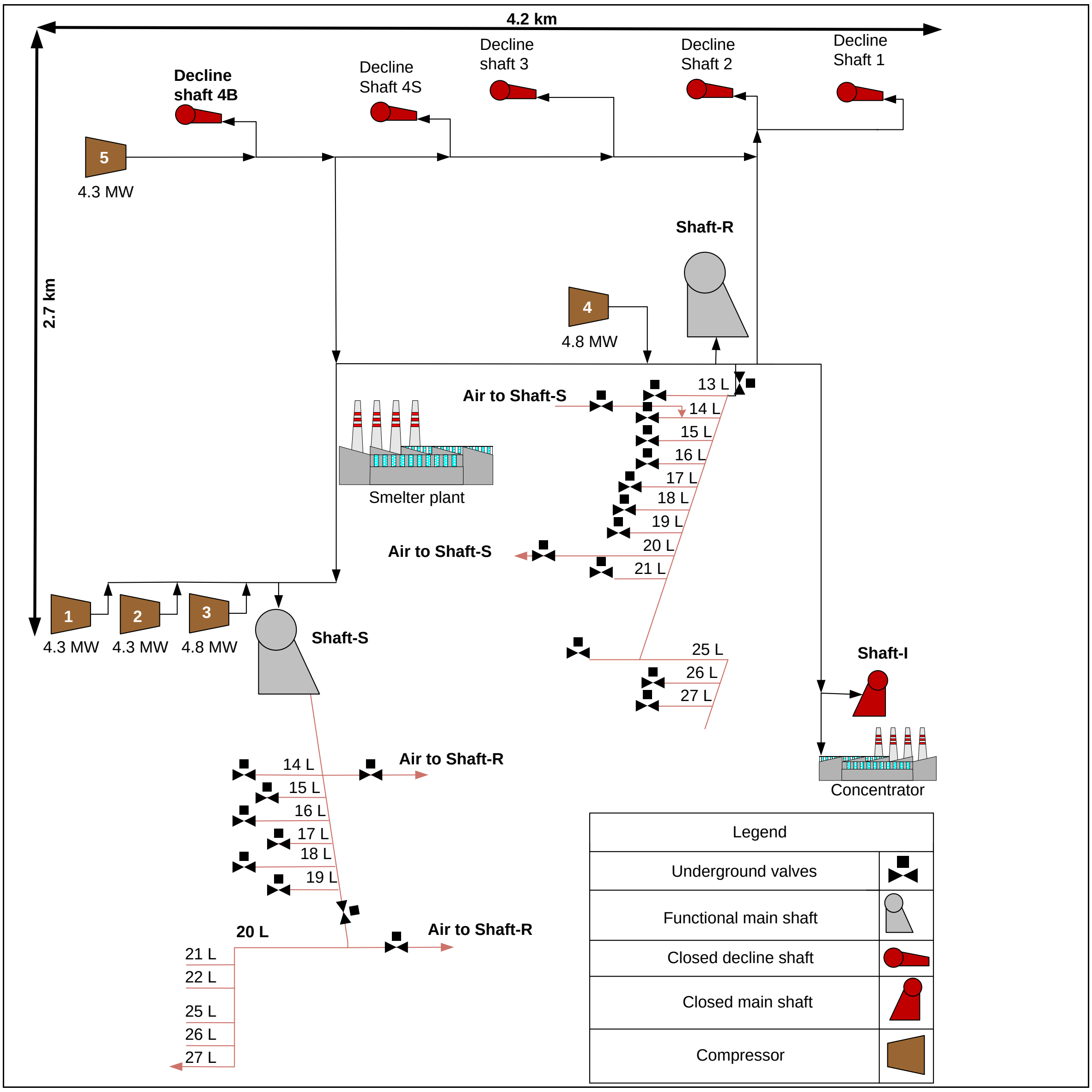


Figure 52: Compressed air system layout of Case Study 1

4.2.2 Step 1: Rank deep-level mine compressed air system of Case Study 1

Overview

The purpose of Step 1 was ranking compressed air systems according to their potential scope for improvement. This was achieved by implementing the solution developed for Contribution 1. Thus, Contribution 1 was implemented according to the methodology process shown in Figure 38. The implementation of Contribution 1 was done using the following steps:

Step 1.1: Collect energy consumption data

An independent M&V team appointed by Eskom developed an energy consumption baseline. This M&V baseline represented what the electricity usage would have been if energy saving initiatives had not been implemented. The baseline data was collected from the supervisory control and data acquisition (SCADA) system by both the M&V team and ESCO involved. The data obtained for the baseline was for three months measured in two-minute intervals. It is shown in half-hour intervals in Appendix B, Table 35.

The peak drilling shift of this specific mine during the baseline period was between 11:00 and 13:30. The peak blasting shift was, however, within the expected period between 18:00 and 20:00. Figure 53 shows the power consumption baseline of Case Study 1.

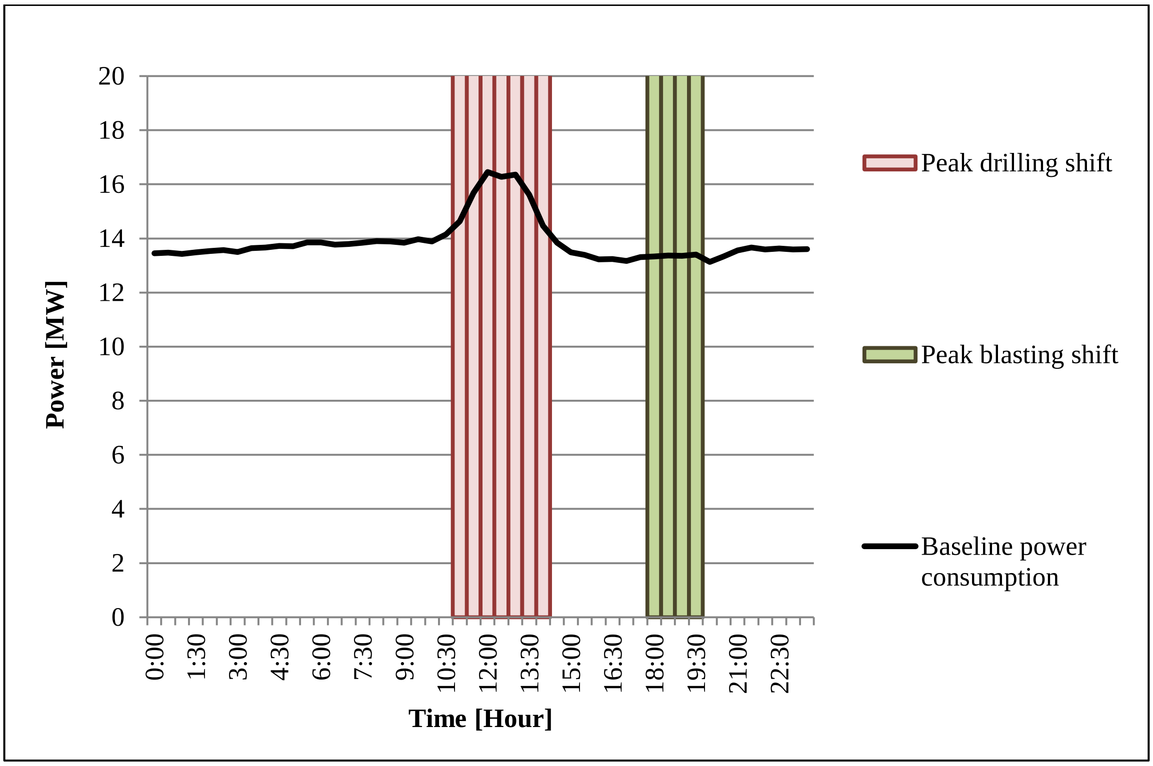


Figure 53: Power consumption profile of the compressed air system in Case Study 1

Step 1.2: Determine pre-implementation ERR

The pre-implementation ERR was determined with Equation 2 using the power consumption data of a typical production day. The average power consumption during the peak drilling shift (d) was calculated as 15.64 MW. The average power consumption during the peak blasting shift (b) was determined as 13.32 MW. Thus, the ERR from the highest energy demand period to the lowest demand period was calculated as 14.8%.

Step 1.3 and Step 1.4: Rate ERR and scope for improvement

The compressed air system pre-implementation ERR of Case Study 1 was compared with the average benchmark ERR. Figure 54 shows the ERR of the compressed air system from Case Study 1 (indicated as the triangle marker). The pre-implementation ERR was below the average benchmark ERR of 25%. Therefore, the compressed air system in Case Study 1 was expected to have an above average benchmark scope for improvement.

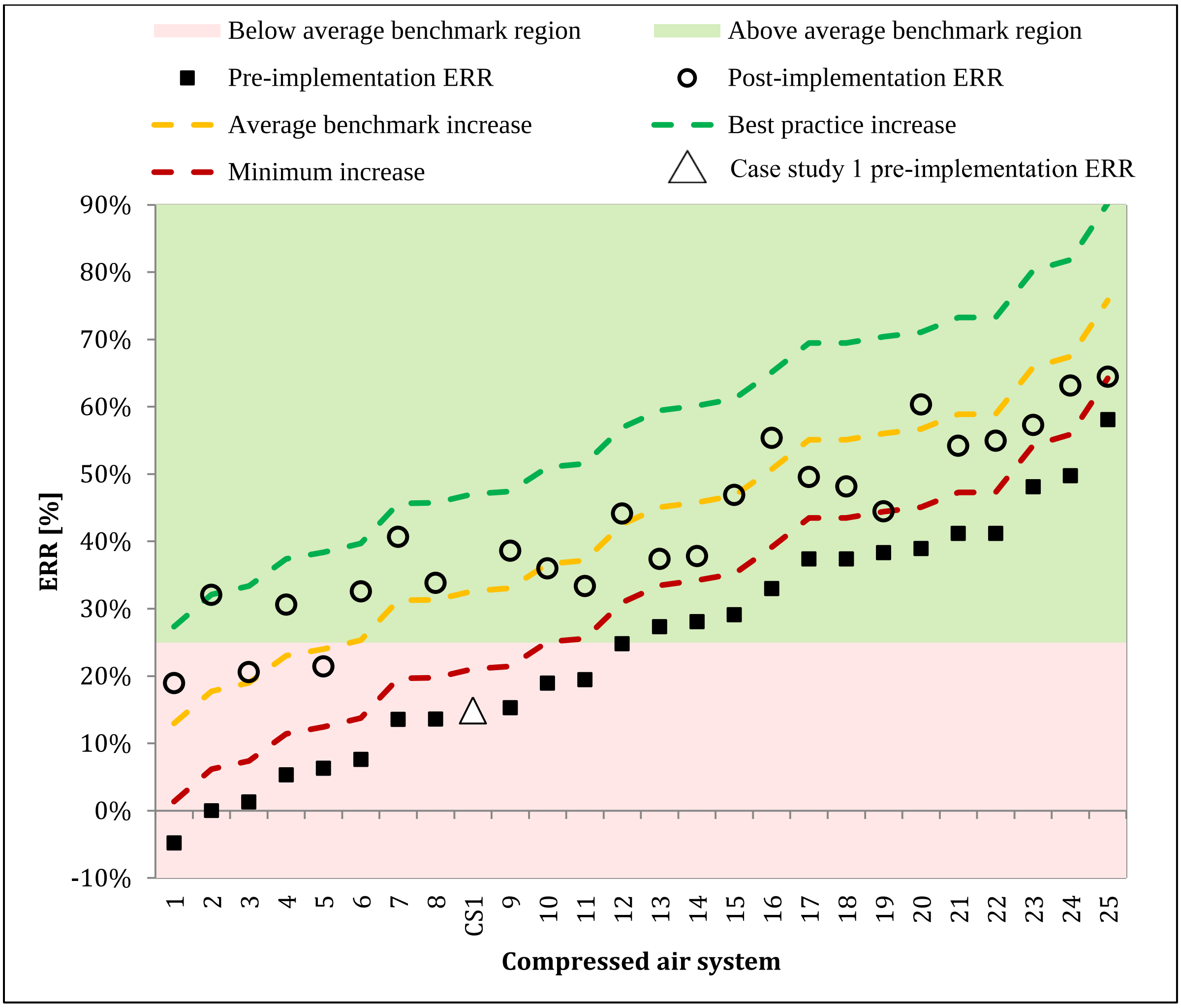


Figure 54: Pre-implementation ERR of Case Study 1 (CS1) compared with the average benchmark

4.2.3 Step 2: Quantify potential energy savings of Case Study 1

Overview

The aim of Step 2 was quantifying the potential scope for improvement on the compressed air system of Case Study 1. The new practical tool developed as Contribution 2 was used to estimate the potential energy saving target. The ESCO predicted an estimated savings target of 1.3 MW with a simulation model developed in KYPipe. However, insufficient flow and pressure data was available as multivariable inputs to determine the potential energy savings.

The M&V team stated in reports that no accurate calculation of estimated demand impacts could be suggested before implementing the energy saving initiatives. Nevertheless, the new simplified tool could quantify the potential energy saving target with only power consumption data as single-variable input. The new simplified tool was implemented in Case Study 1 by following the process previously illustrated in Figure 38. This process was conducted with the following steps:

Step 2.1 and Step 2.2: Estimate expected saving ranges with pre-implementation ERR

The first step (Step 2.1) in the methodology process of Contribution 2 was considering a pre-implementation ERR of 14.8% (determined in Step 2.1) as a single-variable input. For Step 2.2, the minimum, average and maximum expected benchmark ERR increase could be determined with Equation 3, Equation 4 and Equation 5. The results from Step 2.1 and Step 2.4 for Case Study 1 are summarised in Table 26.

Step 2.3: Determine post-implementation ERR with the regression model

The next step (2.3) was using the pre-implementation ERR of 14.8% as the single-variable input in Equation 6. This determined the expected post-implementation ERR with the regression model developed in the methodology process of Contribution 2. As a result, the expected post-implementation ERR was 35%. The result was 2% more than the expected average benchmark increase of 33%. Thus, it could be assumed with high confidence that the energy savings would be within range of the average (2.7 MW) and maximum expected (5 MW) saving as indicated in Table 26.

Step 2.4: Quantify potential energy savings target

With the expected post-implementation ERR from the regression model, the estimated savings target could be determined with Equation 7. The estimated energy saving target determined with the regression model was calculated to be 3.14 MW (see Table 26). This is 0.34 MW more than the expected target based on the average benchmark, and 1.84 MW more than the savings simulated by the ESCO and M&V team.

Table 26: Expected benchmarked ERR increases and savings target for Case Study 1

ERR INCREASE	EXPECTED ERR INCREASE [%]	ESTIMATED SAVINGS [MW]
Minimum benchmark [ERR$_{(Min)}$]	21	1
Average benchmark [ERR$_{(Avg)}$]	33	2.7
Expected saving target	**35**	**3.14**
Maximum benchmark [ERR$_{(Max)}$]	47	5

Summary of simplified high-level investigation on Case Study 1

The power consumption data of the compressed air system in Case Study 1 was readily accessible. It was thus possible to determine the pre-implementation ERR of 14.8%. As a result, the compressed air system in Case Study 1 could be ranked using the novel benchmarking method.

The novel benchmarking method indicated that the compressed air system underperformed when compared with the average benchmark ERRS. Therefore, the scope for improvement was expected to be above the benchmark average. The new simplified quantification tool determined that the average expected benchmark ERR increase was 33% which is a power saving of 2.7 MW.

The regression model approach supported the expected savings with an estimated ERR increase of 35% and a saving target of 3.14 MW. Although insufficient data was available for the ESCO to develop an accurate simulation model, an estimated saving of 3.14 MW was significantly more than the expected savings of 1.3 MW estimated by the ESCO. The findings of simplified high-level investigation methodology discussed in Section 4.2 are verified by comparing the findings with the actual results achieved in Section 4.3.

4.3 Results from energy saving strategy on Case Study 1

4.3.1 Overview

This section discusses the implementation and results of energy saving initiatives implemented on the compressed air system of Case Study 1. An IDM-funded project was approved by Eskom to reduce the energy consumption of the compressed air system during Eskom's evening peak period. The ESCO simulated that a target of 1.3 MW would be achieved. However, the ESCO did state that insufficient data was available to accurately simulate the potential savings. However, the next step was to implement an actual energy saving initiative.

Before any strategies were implemented, a baseline was determined to establish what the operation conditions were before implementing strategies. This provided a measure to compare the impact of strategies to be implemented. The variables considered during the baseline measurement were power, pressure, flow demand, guide vane and blow-off position.

Baseline power consumption

During non-drilling shifts, the mine operated three baseload compressors. During drilling shifts, the flow demand increased, which reduced the pressure. Thus, an extra standby compressor was started to match the air supply with the air demand. A fourth compressor served as a backup compressor in the event of an unplanned compressor breakdown, or if the air demand increased unexpectedly. The location of these compressors is illustrated in the layout shown in Figure 52. Figure 53 shows the power demand profile of the compressed air system throughout the regular production day.

Pre-implementation pressure and flow demand

The average flow and pressure demand were measured during the baseline period to determine the minimum requirements for production during the initial operation. Mine management requested a minimum pressure of 520 kPa to operate all mining operations without limits.

Figure 55 shows that the baseline pressure demand decreased from 600 kPa during low-demand (non-drilling shifts) periods to a minimum of 490 kPa during high-demand periods (drilling shifts). The low pressure of 490 kPa was below the minimum limit of 520 kPa, thus Compressor-2 was started to recover the system pressure to 600 kPa. The average flow demand during non-drilling shifts was 60 000 m^3/h, and 95 000 m^3/h during drilling shifts.

Mine personnel did not conduct tests previously to identify the minimum pressure and flow requirements to operate without limits. This is due to the concern that operating on minimum flow and pressure exposes them to production loss when the pressure and flow supply are below the minimum limits. The mine in Case Study 1 required energy experts to identify the minimum required pressure and flow limits without production losses.

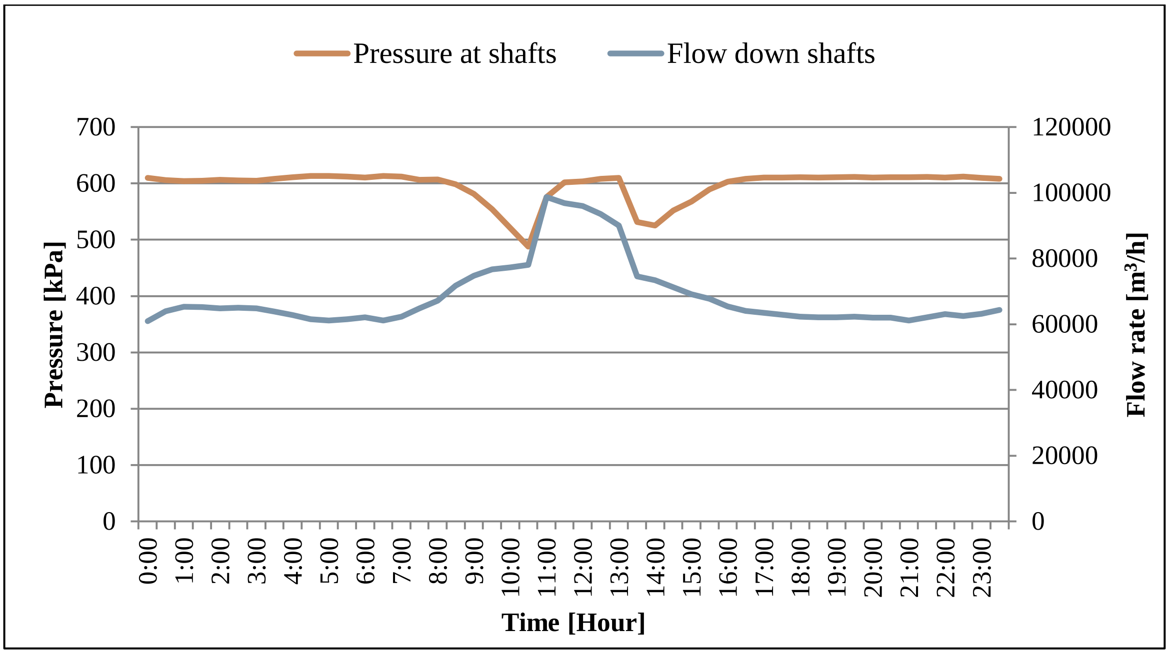


Figure 55: Average pressure- and flow demand to the shafts during original operation

Pre-implementation guide vane position

Compressor-1, Compressor-4, and Compressor-5 operated as baseload compressors. Compressor-1, and Compressor-5, however, cut back the air supply during non-drilling shifts (see Figure 56) to reduce the oversupply of compressed air into the system. The guide vane positions of these two compressors were at a minimum (40%) during non-drilling shifts.

Compressor-4 operated at full load and 100% guide vane angle throughout the regular production day, including high-demand and low-demand periods. Compressor-2 only functioned as a trimming compressor during drilling (high-demand) shifts; therefore, the guide vanes only opened from 0% to 100% during drilling shifts.

Mine personnel involved with Case Study 1 were aware that three compressors in the non-drilling shifts led to an oversupply of air. The additional compressor started during the drilling shift also caused compressor oversupply.

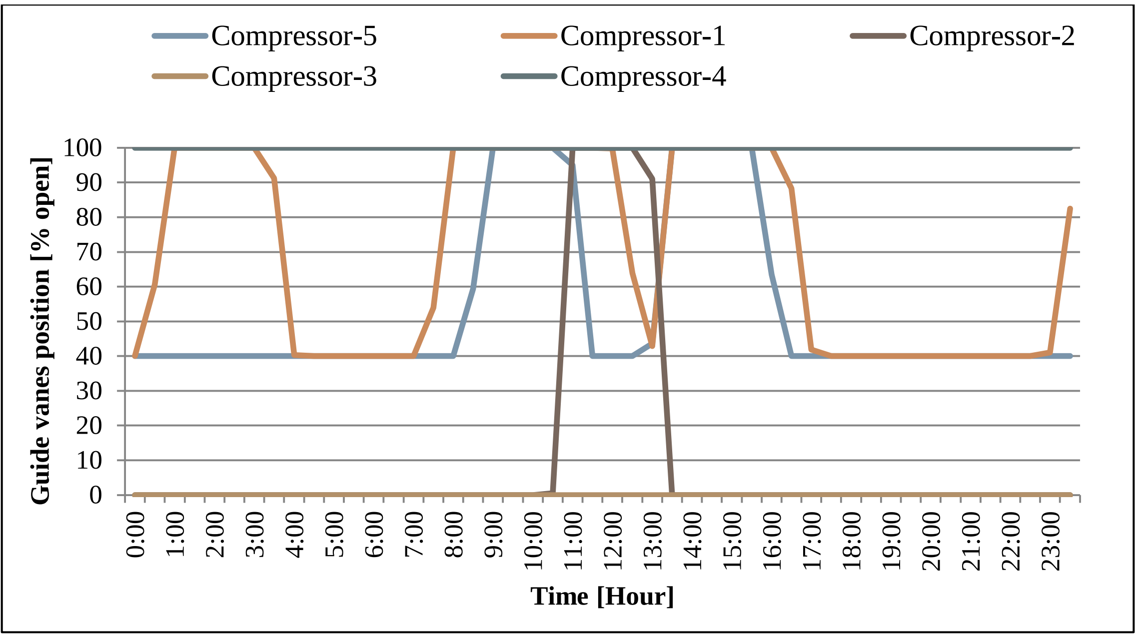


Figure 56: Guide vane positions of compressor operating during normal production day

Pre-implementation blow-off position

Blow-off occurs when a compressor protects itself from surge. Whenever a compressor cannot sufficiently reduce the oversupply of compressed air using guide vanes alone, the oversupply of compressed air is released into the atmosphere through the blow-off valve. During blow-off conditions, the flow and pressure in the system exceed what the compressor can supply.

The blow-off position of each compressor was measured to identify which compressor was most affected by an oversupply of compressed air. Figure 57 shows that Compressor-5's blow-off valve often opened during non-drilling shifts.

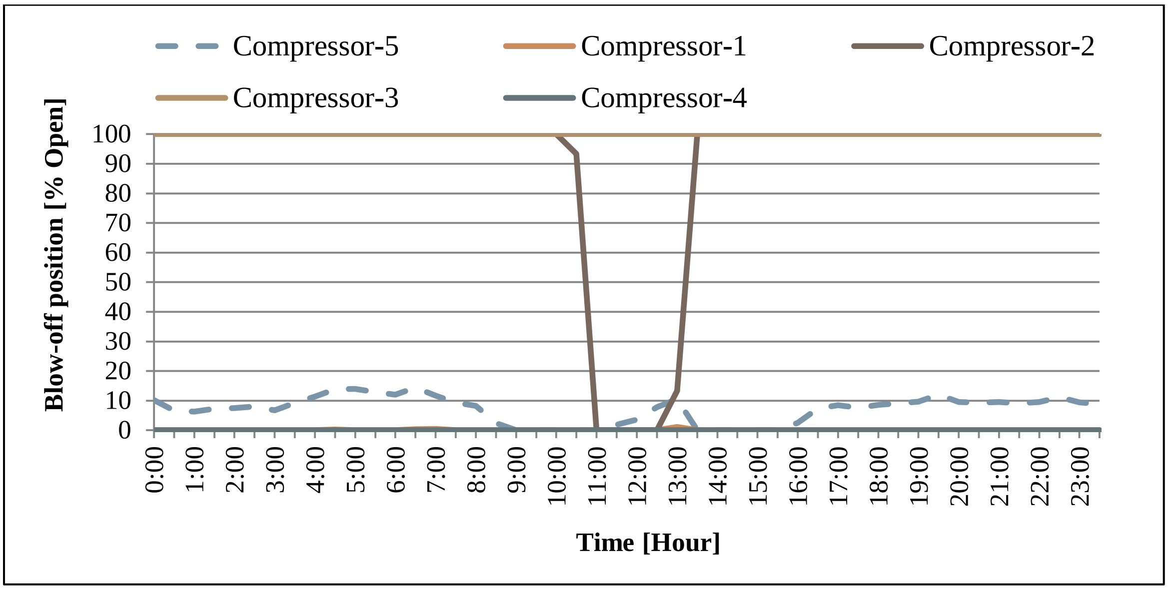


Figure 57: Average blow-off position of the compressors during original operation

4.3.2 *Load clipping test and integrated approach used in Case Study 1*

Overview

Mine management of Case Study 1 agreed to conduct a load clipping test followed by an integrated approach during the peak blasting shift (18:00–20:00) to achieve the Eskom IDM target of 1.3 MW. The load clipping test and integrated approach conducted in Case Study 1 are discussed in Appendix C as follows:

1. **Load clipping strategy test**: Stop a compressor that oversupplies compressed air during Eskom's evening peak period.
2. **Leak repair**: Repair major leaks on a mismanaged compressed air network to improve load clipping test results.
3. **Energy saving strategies implemented after leak repair**: Select optimal compressor combinations for improved savings.
4. **Cost-effective throttle control**: Implement a cost-effective control to reduce oversupply of compressed air.

Results achieved with integrated approach

In Case Study 1, existing techniques were combined to realise potential energy savings. These energy saving initiatives in combination resulted in a significant saving of 2.93 MW during Eskom's evening peak period. An independent M&V team measured and verified the results achieved for this project. Figure 58 shows the impact of the energy saving initiatives compared with the power consumption baseline. Although energy efficiency was achieved the IDM-funding model only rewards load reduction during Eskom evening peak period.

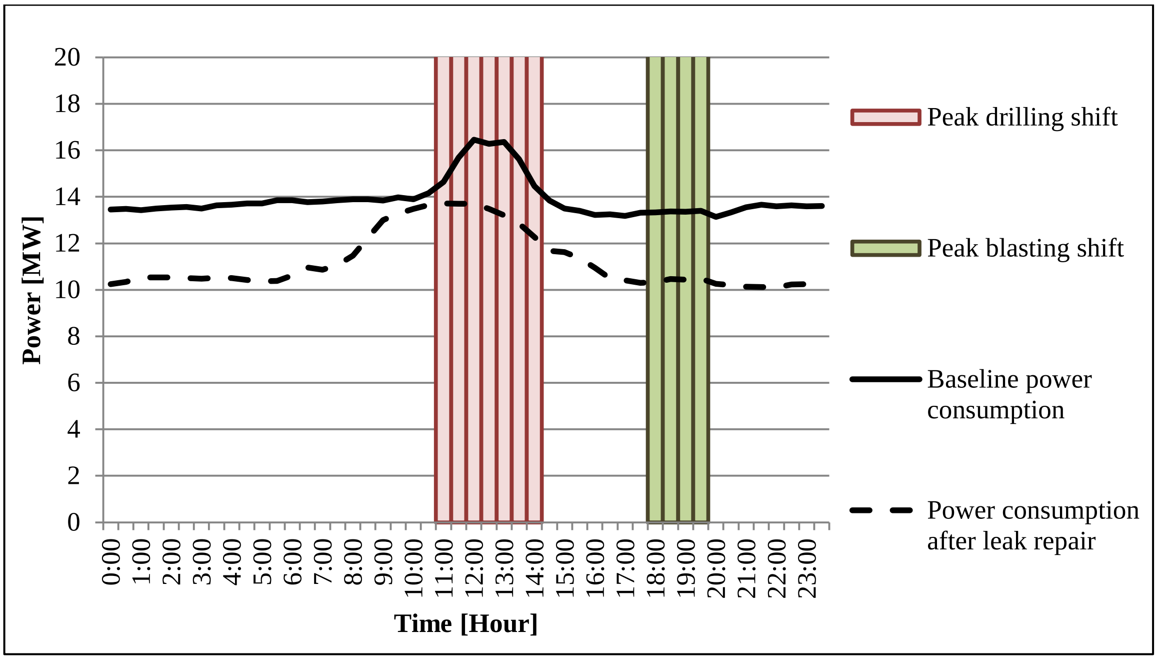


Figure 58: Actual impact of energy saving initiatives implemented in Case Study 1

4.4 Validation of new methodology in Case Study 1

4.4.1 Overview of Case Study 1's results

In this section, the results obtained with the new high-level investigation methodology are compared with both the expected results from the ESCO and the actual results achieved after realising the potential energy savings in Case Study 1.

4.4.2 New investigation methodology on Case Study 1

As expected, power consumption data was readily accessible for Case Study 1. As a result, the pre-implementation ERR could be determined with a single-variable input. Considering the pre-implementation ERR, a generic calculator developed in Microsoft Excel™ could define the following within minutes:

1. **Scope for improvement for Case Study 1 (Contribution 1):** The exiting energy efficiency was below the benchmark average. Thus, the scope for improvement was expected to be an above average expected benchmark saving of 2.7 MW and below the maximum expected saving of 5 MW.
2. **The expected energy saving target (Contribution 2):** The expected target during Eskom's evening peak period and peak blasting shift was estimated to be 3.14 MW.
3. **Simplified high-level investigation methodology (Contribution 3):** With only power consumption as a single-variable input, the new investigation methodology could rate scope for improvement and quantify potential savings within minutes. This enables ESCOs

to determine the feasibility of implementing a potential energy saving project on specific mines.

4.4.3 ESCO/M&V team on Case Study 1

Limited information was available for the ESCO and M&V team to accurately estimate what potential savings existed in Case Study 1. However, the available simulation model used by the ESCO required multivariable data sets. As a result, the projected saving from the ESCO and M&V team was 1.3 MW. After discussing the simulation process with the ESCO and M&V, it was determined that the simulation took an estimated four days to determine a conservative potential energy saving target.

4.4.4 Actual results on Case Study 1

The energy saving was achieved through a combination of energy efficiency and load clipping strategies. These strategies realised an average saving of 2.93 MW during Eskom's evening peak period.

4.4.5 Compare investigation methodology with actual results from Case Study 1

This section compares the findings from the high-level investigation methodology with the actual results achieved in Case Study 1. The findings of Case Study 1 are summarised and compared in Table 27. These results can be discussed as follows:

Scope for improvement (Contribution 1)

The simulation tool used by the ESCO and the M&V team did not consider the benchmark rating of the compressed air system. However, the new high-level investigation methodology includes benchmarking to rank the scope for improvement. It was predicted that the scope for improvement would be between the ranges of average expected benchmark saving of 2.7 MW and maximum expected benchmark saving of 5 MW. This estimation was validated in Case Study 1 with an actual saving of 2.94 MW.

Data sets required to quantify potential energy savings

The ESCO from Case Study 1 required multivariable data sets to simulate and predict the potential savings. The new simplified high-level investigation methodology only required power consumption as a single-variable input.

Estimated saving target accuracy (Contribution 2)

The available multivariable simulation model used by both the ESCO and M&V team estimated a saving target of 1.3 MW during Eskom's evening peak period. However, the actual savings achieved was 2.94 MW. Although the ESCO confirmed that the required data was limited, the actual saving was more than double the estimated savings from the ESCO and M&V team. On the other hand, the simplified high-level investigation methodology included a practical tool for quantifying potential savings. The new tool predicted an actual saving of 3.14 MW, which was accurate within 7%. Therefore, the actual results validated the new tool in Case Study 1.

Time required to quantify potential savings

Considering that insufficient data sets were available during the data acquisition phase of an investigation, skilled simulators in an ESCO used approximately 4 days to develop a simulation model. The new practical tool only required power consumption as an input to estimate and summarise the expected savings within 10 minutes.

Table 27: Validation of new investigation methodology with Case Study 1 results

	ESCO/M&V TEAM	**NEW SIMPLIFIED INVESTIGATION METHODOLOGY (CONTRIBUTION 3)**	**ACTUAL RESULTS**
Compressed air system ranking according to scope for improvement **(Contribution 1)**	–	Above benchmark average	Above benchmark average
Data sets required to quantify potential energy savings	Multivariable data sets	Single-variable data set	
Energy saving target **(Contribution 2)**	1.3 MW	3.14 MW	2.93 MW
Saving quantification accuracy	45%	93%	–
Time required to quantify potential savings target during Eskom evening peak period **(Considering required data sets are readily accessible)**	4 days	10 minutes	–

4.5 Applying the simplified investigation methodology on Case Study 2

4.5.1 *Overview*

The new investigation methodology is systematically implemented on the second case study in this section. Figure 59 illustrates a simplified compressed air system layout used for Case Study 2. The compressed air system consisted of nine compressors that provided compressed air to main shafts Shaft-K1 and Shaft-K2. These nine compressors also supplied a concentrator located on each shaft.

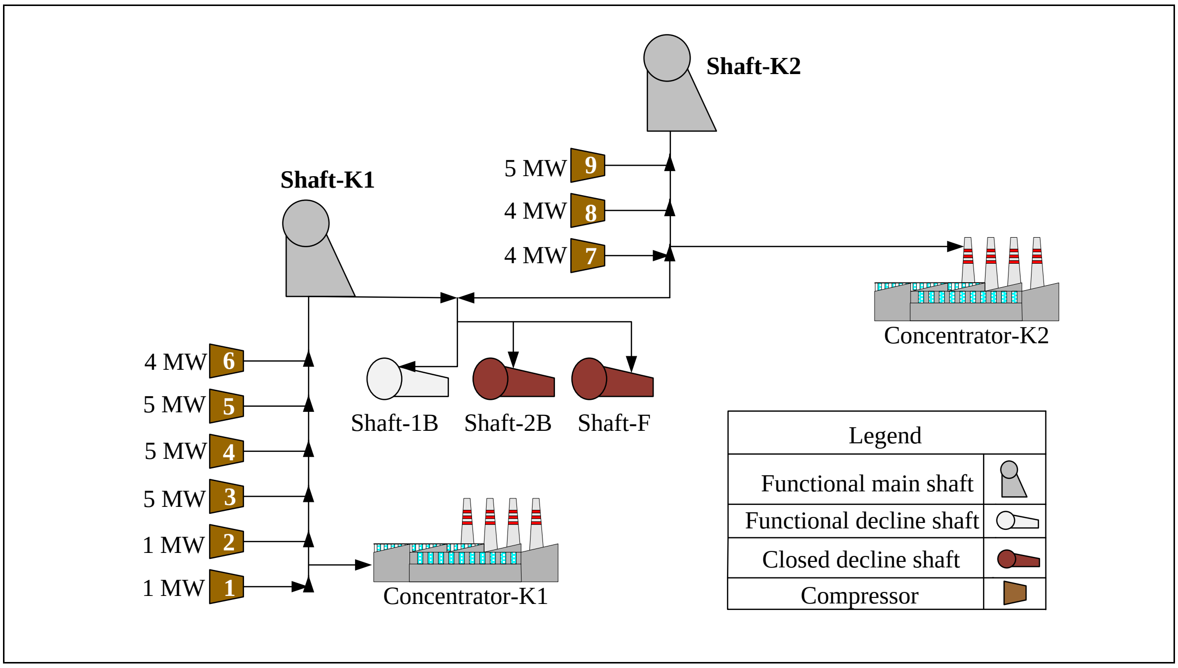


Figure 59: Compressed air system layout of Case Study 2

4.5.2 *Step 1: Rank deep-level mine compressed air system of Case Study 2*

Overview

Step 1 ranked the compressed air system of Case Study 2 according to its potential scope for improvement. This was achieved by implementing the novel simplified benchmarking method developed as Contribution 1. The implementation of Contribution 1 was done according to the steps of the methodology process illustrated in Figure 38.

Step 1.1: Collect energy consumption data

This baseline data represented what the electricity usage would have been without implementing energy saving initiatives. The baseline data was collected from the SCADA system by the M&V team and ESCO involved (see Appendix B, Table 36).

As expected, the peak drilling shift of this specific mine during the baseline period was between 09:00 and 12:00. The peak blasting shift was, however, between 16:30 and 18:00. Figure 60 shows the power consumption baseline of Case Study 2.

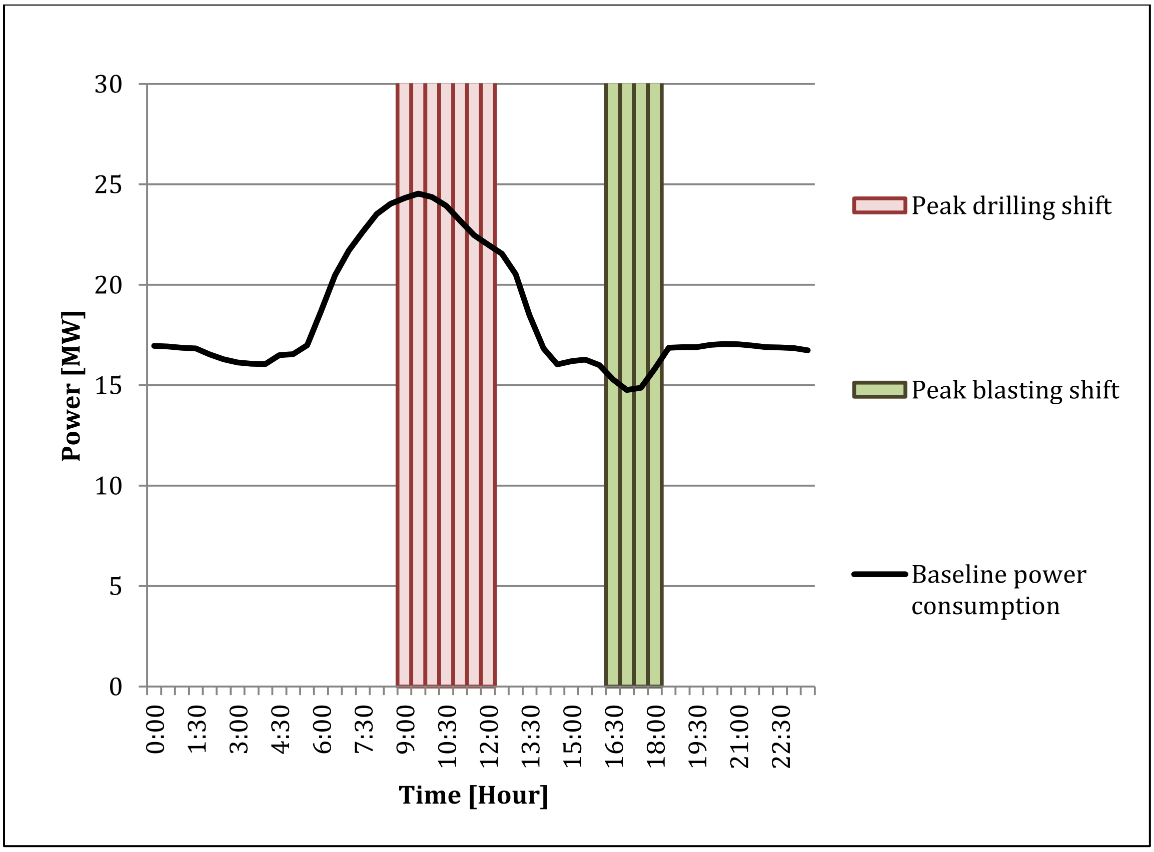


Figure 60: Power consumption profile of the compressed air system in Case Study 2

Step 1.2: Determine pre-implementation ERR

Equation 2 was used to determine the pre-implementation ERR with the energy consumption baseline of a normal production day. The average power consumption during the peak drilling shift (d) was calculated as 23.8 MW. The average power consumption during the peak blasting shift (b) was determined as 15.2 MW. Therefore, the ERR from the highest energy demand period to the lowest demand period was calculated as 36.1%.

Step 1.3 and Step 1.4: Rate ERR and scope for potential improvement

The pre-implementation ERR of Case Study 2 was compared with the average benchmark ERR to rate the compressed air system. The pre-implementation ERR of 36.1% (indicated with a triangle marker in Figure 61) was above the average benchmark ERR of 25%. Thus, the scope for improvement was expected to be below the average benchmark ERR increase.

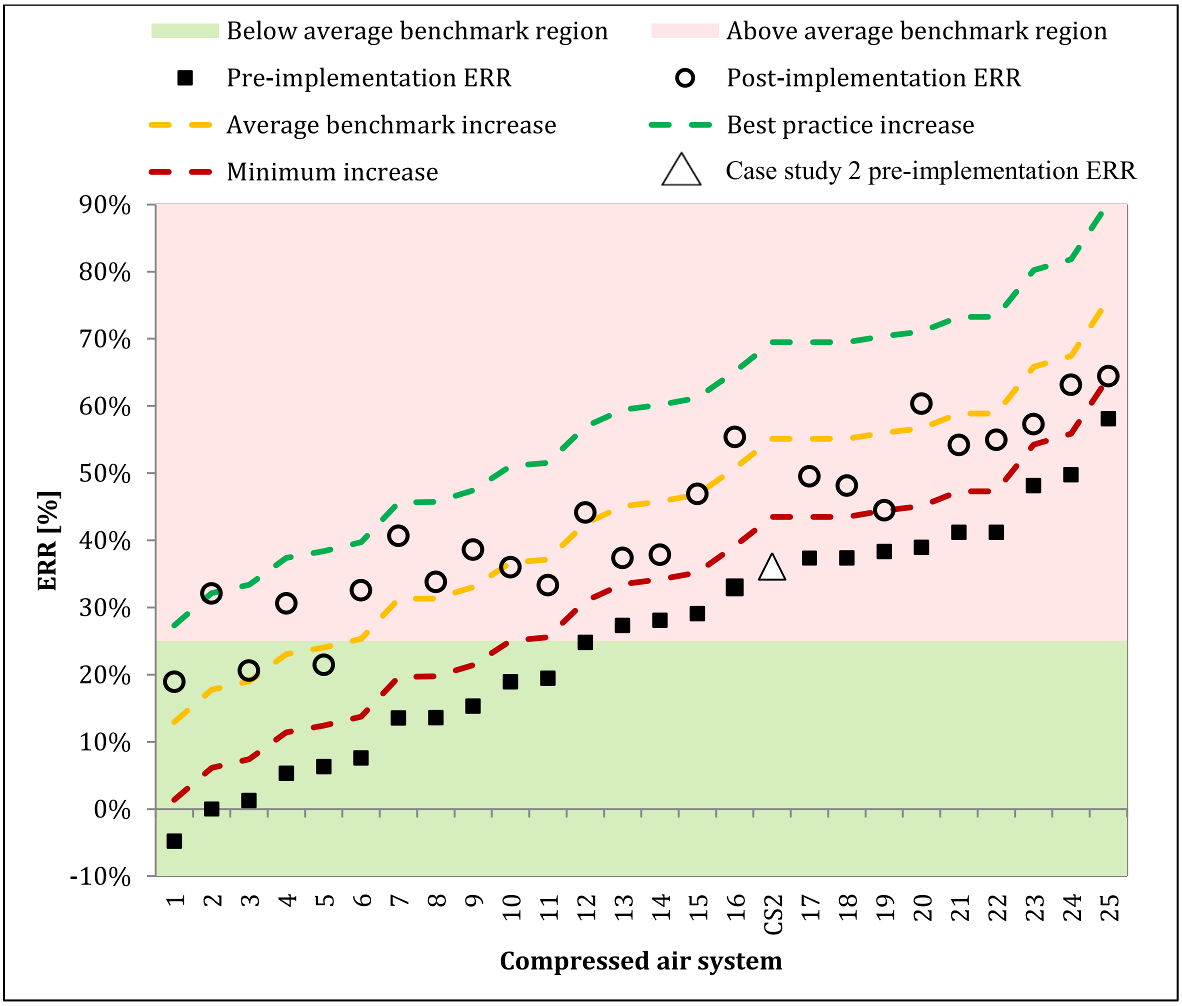


Figure 61: Pre-implementation ERR of Case Study 2 compared with the average benchmark

4.5.3 *Step 2: Quantify potential energy savings of Case Study 2*

Overview

The simplified tool developed as Contribution 2 was used to quantify the potential energy savings on the compressed air system of Case Study 2. The methodology process of the new simplified investigation methodology shown in Figure 38 was followed by the following steps:

Step 2.1 and Step 2.2: Estimate expected savings target with pre-implementation ERR

With power consumption as a single-variable input, a pre-implementation ERR of 36.1% was determined. For Step 2.2, the minimum, average and maximum expected benchmark ERR increase and savings target could be determined with Equation 3, Equation 4 and Equation 5. These expected benchmark ERR increase results for Case Study 2 are summarised in Table 28.

Step 2.3: Determine post-implementation ERR with the regression model

Equation 6 was used with the pre-implementation ERR of 36.1% to estimate the expected post-implementation ERR of 50.1% with the regression model developed for Contribution 2. Based on the novel benchmark rating, it could be assumed that the actual ERR increase would be within the range of the minimum (1.5 MW) and average benchmark increase (4.07 MW) as indicated in Table 28.

Step 2.4: Quantify potential energy savings target

The estimated potential energy savings was determined with Equation 7 by using the post-implementation ERR determined with the regression model. Thus, considering an expected post-implementation ERR of 50.1%, a power saving of 3.32 MW was predicted.

Table 28: Expected benchmark ERR increase and savings target for Case Study 2

ERR INCREASE	EXPECTED ERR INCREASE [%]	ESTIMATED SAVINGS TARGET [MW]
Minimum benchmark [ERR$_{(Min)}$]	42	1.50
Expected saving target	**50**	**3.32**
Average benchmark [ERR$_{(Avg)}$]	53	4.07
Maximum benchmark [ERR$_{(Max)}$]	68	7.60

4.5.4 Summary of high-level investigation on Case Study 2

The readily accessible power consumption data was used as a single-variable input to determine the pre-implementation ERR of 36.1%. The result was then used to rate the compressed air system with the new simplified benchmarking method. The new benchmarking method indicated that the pre-implementation ERR was above the average benchmark ERR. Thus, it could be determined that the scope for improvement was expected to between the minimum expected increase of 1.5 MW and the average benchmark improvement of 4.07 MW.

The new practical tool indicated an expected savings of 3.32 MW with an estimated ERR increase of 50.1%. This corresponded with the expected scope for improvement rated with the novel benchmarking method. These estimated savings will be compared with the projected savings determined by the ESCO and the actual savings realised by implementing energy saving strategies in Case Study 2.

4.6 Results from energy saving strategy on Case Study 2

4.6.1 *Overview*

An energy saving initiative was implemented by an ESCO on the compressed air system of Case Study 2. The energy saving initiative included a load clipping strategy during the peak blasting period. The ESCO conducted a load clipping strategy, thereby reducing the pressure supply during non-drilling shifts, which included the blasting period and Eskom's evening peak period. The results from this load clipping strategy are discussed in this section.

4.6.2 *Load clipping strategy conducted during peak blasting shift on Case Study 2*

Overview

The load clipping strategy from Case Study 2 included reducing the pressure set points for Shaft-K1 and Shaft-K2 during peak blasting shifts. Table 29 shows the change in set points during drilling and non-drilling shifts. The reduced pressure set points enabled the baseload compressors operating during non-drilling shifts to further throttle the air supply. The reduced airflow decreased the load on the compressors, which resulted in energy savings.

Table 29: Energy saving initiative implemented on the compressed air system of Case Study 2

	PRE-IMPLEMENTATION PRESSURE [kPa]	POST-IMPLEMENTATION PRESSURE [kPa]
Drilling shift	620	620
Non-drilling shift (peak blasting period)	500	420

Expected from ESCO

The ESCO developed a simulation model after conducting a detailed audit to collect the required multivariable data sets for the simulation model. An in-house simulation software was used by the ESCO to predict an estimated additional saving of 3.83 MW during peak blasting period (see simulation layout in Appendix D, Figure 89).

Actual saving from ESCO

Figure 62 shows the impact of reducing the pressure set points during the peak blasting shift. The actual impact was 3.25 MW during the peak blasting shift. Thus, the simulation was accurate within 16% when compared with the expected saving of 3.83 MW during Eskom evening peak period.

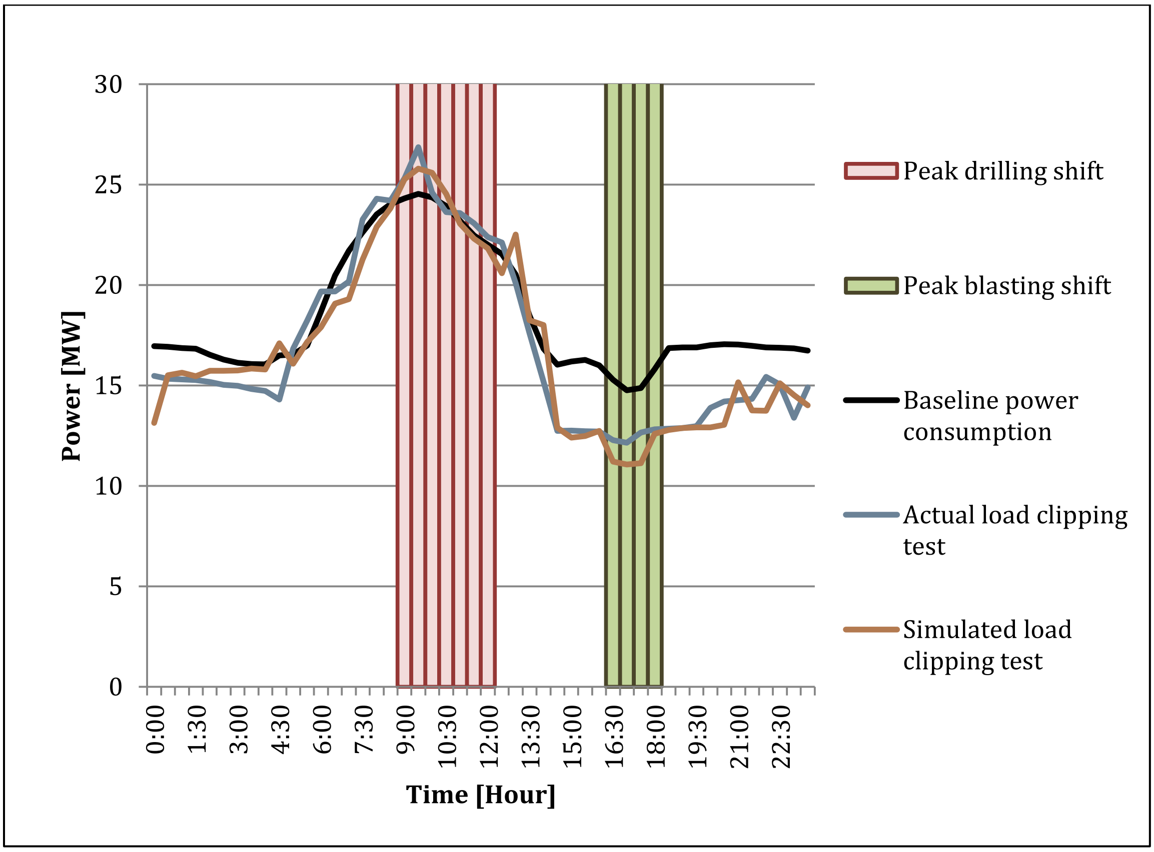


Figure 62: Load clipping impact on compressed air system including Shaft-K1 and Shaft-K2

4.7 Validation of new methodology in Case Study 2

4.7.1 Overview of Case Study 2 results

In this section, the results obtained from the new simplified methodology process, the expected results from the ESCO and the actual results achieved from Case Study 2 are discussed and compared to verify the contributions developed in this study.

4.7.2 New investigation methodology results on Case Study 2

Power consumption data was readily accessible for Case Study 2. As a result, the pre-implementation ERR of Case Study 2 could be determined with a single-variable input. Considering the pre-implementation ERR of 36.1%, the simplified high-level investigation methodology could determine the following within minutes:

1. **Scope for improvement for Case Study 2 (Contribution 1):** The exiting energy efficiency was above the benchmark average. Thus, the scope for improvement was expected to between the ranges of the minimum expected benchmark saving of 1.5 MW and the the average expected saving of 4.07 MW.

2. **The expected energy saving target (Contribution 2):** The expected energy savings target during peak blasting shift was estimated to be 3.32 MW.
3. **Simplified high-level investigation methodology (Contribution 3):** With only power consumption as a single-variable input, the new investigation methodology could rate scope for improvement and quantify potential savings within minutes. This enables ESCOs to determine the feasibility of implementing a potential energy saving project on specific mines.

4.7.3 ESCO results for Case Study 2

All required multivariable data sets were available for the ESCO and M&V team to develop simulation models. This model was used to predict potential savings in Case Study 2. As a result, the projected saving during the peak blasting period from the ESCO was 3.83 MW. After discussing the simulation process with the ESCO, the simulation model was developed over a period of 12 days to determine a potential energy saving target accurately.

4.7.4 Comparing the ESCO and new investigation method

Load clipping strategy conducted during peak blasting shift

The findings and results from Case Study 2 are summarised and compared in Table 30. These results can be discussed as follows:

Scope for potential saving: The new benchmarking method (Contribution 1) used in the simplified high-level investigation methodology identified that the scope for improvement would be between the minimum expected benchmark saving of 1.5 MW and the average expected benchmark saving of 4.07 MW. The actual saving during the peak blasting shift was 3.25 MW for Case Study 2. Thus, the predicted scope for improvement was true for Case Study 2.

Data sets required for investigations: The simulation required multivariable data sets for development. The new simplified high-level investigation methodology only required power consumption as a single-variable input.

Estimated savings target (Contribution 2): The ESCO predicted a potential saving of 3.85 MW during the peak blasting period. The new tool for quantifying potential energy savings predicted that an estimated saving of 3.32 MW could be achieved.

Actual savings: The ESCO realised a saving of 3.25 MW during the peak blasting period from 16:30 to 18:00.

The accuracy of predicted savings: The simulated saving of 3.83 MW from the ESCO was accurate within 16% of predicting the actual savings of 3.25 MW during the peak blasting shift.

The new practical tool predicted the saving of 3.32 MW during the peak blasting shift within an accuracy of 2%.

Time required to determine potential saving: Considering that all required data was available, previously the ESCO needed 12 days to simulate the potential savings. The new tool quantified the potential savings (Contribution 1) within an estimated 10 minutes.

Table 30: Results achieved in during blasting shift in Case Study 2

	ESCO/M&V TEAM	NEW SIMPLIFIED HIGH-LEVEL INVESTIGATION METHODOLOGY (CONTRIBUTION 3)
Scope for potential saving (Contribution 1)	–	Below average benchmark increase
Data sets required to quantify potential energy savings	Multivariable data sets	Single-variable data set
Estimated savings target (Contribution 2)	3.83 MW	3.32 MW
Actual savings	3.25 MW	–
Accuracy of predicted saving compared with actual results	84.9%	98%
Time required to determine potential saving	12 days	10 minutes

Load clipping strategy conducted during the Eskom peak period

The peak blasting shifts (16:30–18:00) in Case Study 2 was not within Eskom's evening peak period (18:00–19:30). The focus of this study is quantifying potential energy savings during Eskom's evening peak periods as current IDM-funded projects reward load reduction during this period. Thus, an additional validation was done for Case Study 2 during Eskom's evening peak period. The average power consumption during the peak drilling shift (d) was calculated as 23.8 MW. The average power consumption during the peak blasting shift (b) was determined to be 16.6 MW.

The validation process was repeated for the savings during Eskom's evening peak period. The results are summarised and compared in Table 31. The results in Table 30 support the validation of the new methods and tools developed for this study. The pre-implementation ERR during Eskom's evening peak period (30.3%) was an estimated 5.8% less compared with the pre-implementation ERR during the peak blasting period (36.1%). Considering a pre-implementation ERR, the predicted saving during Eskom evening peak period was 3.72 MW, which was 0.4 MW more than the expected saving during the peak blasting shift. As a result, the practical tool was accurate within 12.6% during Eskom's evening peak period. However, the practical tool was 2% more accurate than the simulated prediction of 3.83 MW.

Table 31: Results achieved in Eskom evening peak period in Case Study 2

	ESCO/M&V TEAM	NEW SIMPLIFIED HIGH-LEVEL INVESTIGATION METHODOLOGY (CONTRIBUTION 3)
Scope for potential saving (Contribution 1)	–	Below average benchmark increase
Data sets required to quantify potential energy savings	Multivariable data sets	Single-variable data set
Estimated savings target (Contribution 2)	3.83 MW	3.72 MW
Actual savings	3.25 MW	–
Accuracy of predicted saving compared with actual results	85%	87%
Time required to determine potential saving	12 days	10 minutes

4.8 Holistic application

4.8.1 *Overview*

This section illustrates a different approach that could be considered with the new simplified investigation methodology. The available data from the 25 compressed air systems previously used to develop the new methods and tools are combined to apply the new methodology on a holistic application. Therefore this section only illustrates an alternative application for the new high-level investigation to identify potential missed opportunities.

4.8.2 *Combined power consumption from available compressed air systems*

The combined power consumption from the available 25 compressed air systems before implementing energy saving projects was calculated and compared with the power usage after implementing energy saving projects. This available power consumption data included the total electricity usage during peak blasting shift (high-demand period) and the peak drilling shift (low-demand period) (see Table 32). The peak blasting shift was typically within Eskom's evening peak period.

The available combined power consumption data was used a single-variable input with a calculator developed in Microsoft Excel™ (see illustration in Appendix E, Table 37). The combined power consumption equated to a pre-implementation ERR of 30%. Therefore, the total power usage pre-implementation ERR was above the average benchmark ERR of 25%. Thus, the holistic scope for improvement was expected to be between the ranges of the minimum expected saving of 28 MW and average expected benchmark saving of 79.4 MW.

The new practical tool estimated that the savings should be 73.3 MW after implementing energy saving projects on all 25 compressed air systems. This was accurate within 9% when compared with the actual total saving of 67.3 MW reported by M&V teams (see Table 32). This corresponded with the below average scope for improvement previously identified with the new benchmarking method (Contribution 1).

Table 32: Total power consumption of 25 available compressed air systems

	TOTAL POWER CONSUMPTION DURING PEAK DRILLING SHIFT (HIGH-DEMAND PERIOD) [MW]	TOTAL POWER CONSUMPTION DURING PEAK BLASTING SHIFT (LOW-DEMAND PERIOD) [MW]
Before implementation of energy saving projects	467.3	326.9
After implementation of energy saving projects	425.1	259.6
Actual saving [MW]	42.3	67.3
Predicted saving [MW]	-	73.3

Figure 63 indicates the minimum, average and maximum expected benchmark savings for the combined 25 compressed air systems. However, considering with maximum expected benchmark saving (best practice improvements), the savings target could be 149.5 MW. Thus, an additional potential saving of 82.2 MW could be realised during Eskom's evening peak period. This equates to an estimated annual cost saving of R60 million (based on Megaflex tariffs 2017/2018). Therefore, it could be considered worthwhile for ESCOs to re-evaluate the estimated missed opportunities from the previous 25 energy saving projects.

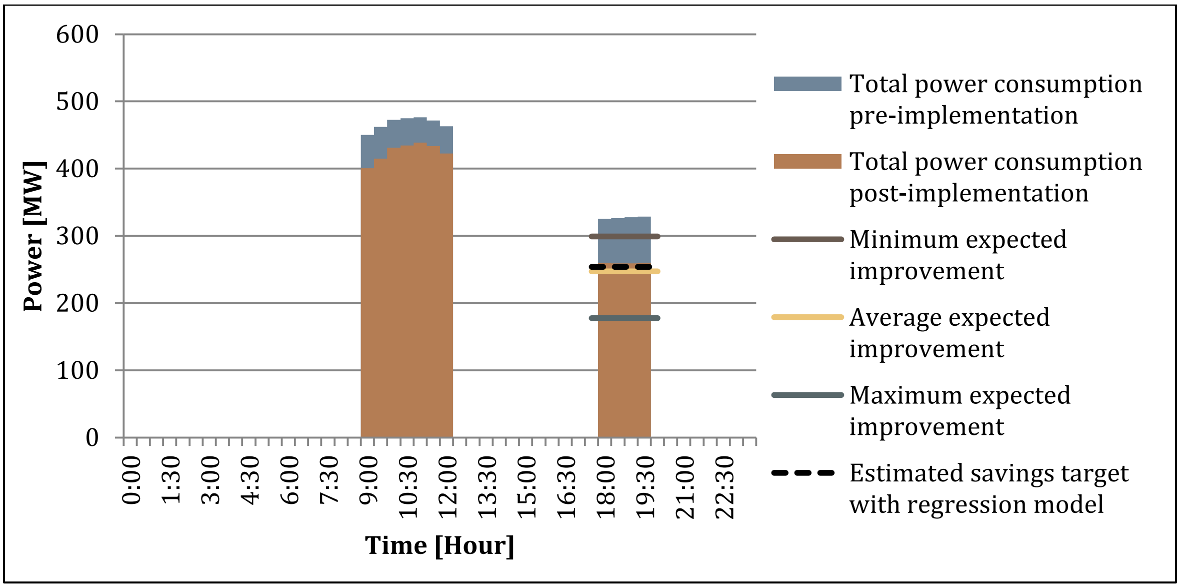


Figure 63: Illustration of potential missed opportunity from existing compressed air systems

4.8.3 Potential approach for with new investigation methodology

The holistic application can be used a simplified method for determining potential missed opportunities available from previous DSM projects implemented on compressed air systems.

4.9 **Conclusion**

In this chapter, the contributions of this study were combined to be implemented as a new simplified high-level investigation methodology on two actual deep-level mines in South Africa. The high-level investigation results were compared with actual results from two case studies to validate the contributions of this study. Firstly, the pre-implementation ERRs of the two compressed air systems were compared with the average benchmark ERR of 25%. Case Study 1 operated below the average pre-implementation ERR which indicated that the savings would be between the ranges of an average expected benchmark saving of 2.7 MW and the maximum expected benchmark saving of 5 MW.

The expected scope for improvement was confirmed with an actual saving of 2.94 MW. Case Study 2, on the other hand, indicated that less than the expected benchmark average (4.07 MW) would be achieved with a minimum expected benchmark saving of 1.5 MW. This was confirmed with the actual improvement of 3.25 MW. Thus, the novel benchmarking method based the pre-implementation ERR was validated (Contribution 1).

After benchmarking each compressed air system, the available savings during Eskom's evening peak were quantified with the new practical tool (Contribution 2). The new practical tool predicted a saving of 3.14 MW for Case Study 1.

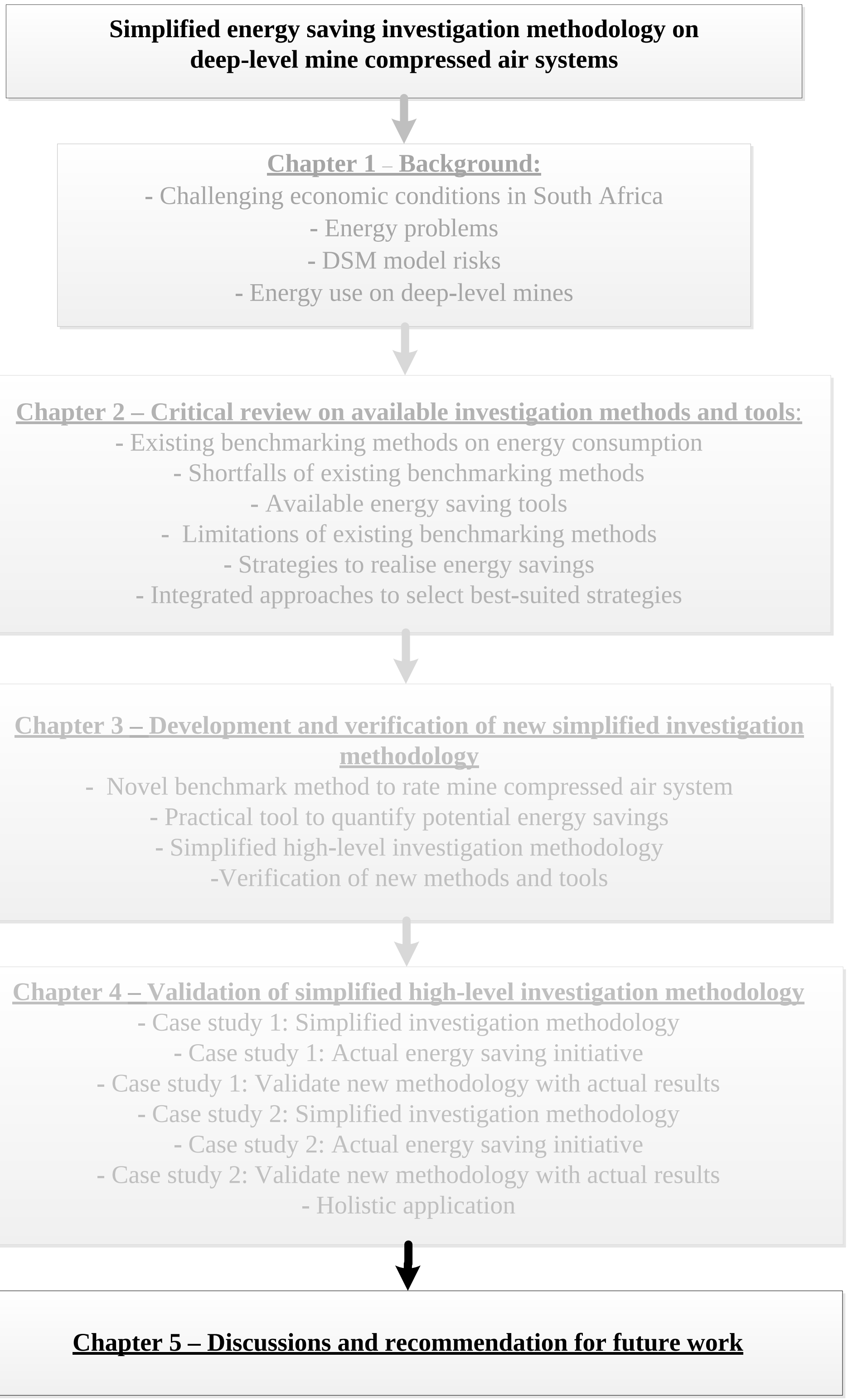
The actual saving of 2.94 MW for Case Study 1 validated the new practical tool with an accuracy of 93%. The ESCO estimated a saving of 1.3 MW for Case Study 1, which is less than half of the actual saving.

The poor estimation from the ESCO is assumed to be due to the limited data that was available for the simulation model. Therefore, a conclusion is made that the new simplified tool is more effective and accurate than previous investigations given the limited data and resources available.

The savings estimation for Case Study 2 was also validated. Due to the peak drilling shift that does not correspond with Eskom's evening peak period, a validation study was conducted for both periods. Compared with the actual savings, the new simplified tool was 98% accurate to predict the available savings within the peak drilling shift of Case Study 2. During Eskom's evening peak period, the new simplified tool was 87% accurate and 2% more accurate than the simulation results from the ESCO.

In summary, the two contributions in combination validated the impact of the new high-level investigation methodology as a third contribution. The new high-level investigation methodology can deliver the required results within minutes and with acceptable accuracy compared with the conventional investigation process that would typically require a minimum of four days considering that all the required data is available. The new simplified tool was additionally implemented on a holistic application including 25 available compressed ait systems. The simplified investigation methodology identified a potential missed savings opportunity of R60 million based on previous best practice improvements. Eskom could consider this approach when introducing new IDM funding initiatives.

5 DISCUSSIONS AND RECOMMENDATION FOR FURTHER WORK



Simplified energy saving investigation methodology on deep-level mine compressed air systems

Chapter 1 – Background:
- Challenging economic conditions in South Africa
- Energy problems
- DSM model risks
- Energy use on deep-level mines

Chapter 2 – Critical review on available investigation methods and tools:
- Existing benchmarking methods on energy consumption
- Shortfalls of existing benchmarking methods
- Available energy saving tools
- Limitations of existing benchmarking methods
- Strategies to realise energy savings
- Integrated approaches to select best-suited strategies

Chapter 3 – Development and verification of new simplified investigation methodology
- Novel benchmark method to rate mine compressed air system
- Practical tool to quantify potential energy savings
- Simplified high-level investigation methodology
-Verification of new methods and tools

Chapter 4 – Validation of simplified high-level investigation methodology
- Case study 1: Simplified investigation methodology
- Case study 1: Actual energy saving initiative
- Case study 1: Validate new methodology with actual results
- Case study 2: Simplified investigation methodology
- Case study 2: Actual energy saving initiative
- Case study 2: Validate new methodology with actual results
- Holistic application

Chapter 5 – Discussions and recommendation for future work

5.1 Summary

The background of this study highlighted the current economic conditions and energy challenges that affect the sustainability of marginal deep-level mines in South Africa. Thus, a need exists to reduce the operating cost on marginal mines to increase profitability. Deep-level mine compressed air systems are often mismanaged, which result in energy wastage in the form of oversupply. Therefore, ESCOs have identified compressed air systems as an area with significant potential for reducing the operating costs of deep-level mines.

Old IDM-funded projects motivated both the ESCO and the client to reduce power consumption. However, available funding at that time enabled clients to afford energy experts from ESCOs to optimise compressed air networks by reducing the oversupply of compressed air. Due to the current economic conditions, funding for energy saving initiatives has reduced significantly while the capital of marginal mines has also minimised. Therefore, marginal mines cannot afford energy experts anymore.

Although the available funding for energy saving initiatives has reduced, clients still expect ESCOs to deliver the same savings impact as they did when large budgets were available. ESCOs are thus required to risk the resources required to optimise compressed air systems. As a result, it is not feasible for ESCOs to investigate all potential energy saving projects.

Extensive audits and simulations are needed during investigations to determine the viability and potential impact of the various energy saving initiatives. Research was conducted on the current methods and tools used during investigations to identify their shortfalls. The research found that existing methods and tools used during investigations are costly, time-consuming and require skilled labour. This requires significant resources and highlights the need for ESCOs to investigate potential energy savings with reduced risks and input.

The first objective of this study was developing simplified methods and tools for investigating potential energy saving projects. These simplified methods and models included a new simplified benchmarking method for ranking compressed air systems (Contribution 1) and a practical tool for quantifying potential energy saving targets (Contribution 2). The second objective of this study was combining the simplified methods and tools developed for Objective 1. In combination, these methods and tools delivered a new simplified high-level investigation methodology (Contribution 3).

This new investigation methodology will enable ESCOs to minimise risk and input during investigations on deep-level mine compressed air systems and related M&V procedures. Therefore, with the contributions from this study, it would be feasible for ESCOs to investigate more potential energy savings projects.

The new methods and tools were verified by comparing the contributions of the study with available methods and tools previously used in other studies. The studies selected for the verification were based on the availability of data to compare the results of the existing and the new methods and tools.

After verification, the contributions were validated by implementing the contributions as a new simplified high-level investigation methodology on two actual deep-level mines compressed air systems. The impact of the new simplified high-level investigation methodology was highlighted in these case studies. The high-level investigation results were compared with actual results from the case studies to validate the contributions of this study. These results corresponded with the expected results determined through the simplified high level investigation methodology.

In conclusion, the two contributions in combination validated the impact of the new high-level investigation methodology. The new high-level investigation methodology can deliver the required results within minutes and with acceptable accuracy compared with the conventional investigation process that typically requires a minimum of four days if all the required data is available.

The new investigation methodology was further implemented on a holistic application as an illustration to identify potential missed energy saving opportunities on 25 existing compressed air energy saving projects. As a result, it was determined that an additional saving of 82.7 MW could be realised during Eskom’s evening peak period. This equates to an approximate annual cost saving of R60 million.

Ultimately, the new simplified high-level investigation methodology developed in this study reduces the risks and input required from ESCOs to investigate more potential energy saving projects. This will aid marginal mines that cannot afford energy experts (ESCOs) due to financial constraints. As a result, the new methodology can contribute to the sustainability of marginal mines by enabling ESCOs to investigate more potential energy saving projects with limited time, funding and resources.

5.2 Recommendations for further work

5.2.1 Overview

This study focused on a high-level investigation methodology for compressed air systems to identify potential energy savings within peak blasting periods. The results of the new simplified investigation methodology proved to be effective and sufficiently accurate. However, it is recommended that further work should be conducted to apply this methodology to other non-drilling periods.

Although the new high-level investigation methodology determines the scope for potential energy savings, it does not indicate by how much the compressed air demand must be reduced to realise the potential savings. It is recommended that further work should be done to quantify the reduction of the compressed air demand to realise the potential scope for improvement. This will enable an ESCO to identify best-suited strategies to reduce the compressed air demand according to the potential scope.

IDM funding models previously rewarded load reduction on a variety of high-demand systems used in the mining and industrial sector. It is recommended to apply the new high-level methodology to other high-demand systems for further work. Recommendations for these systems are discussed further in this section. These high-demand systems include compressors in other industries, and dewatering and ventilation systems within deep-level mines.

5.2.2 Compressed air usage within other industries

The deep-level mining industry is one of many large contributors to high electricity consumption in South Africa. However, other industries such as steel manufacturing, cement production and chemical companies play an important role in the ever-increasing power demand. Compressed air systems are also one of the largest expenses within these industries. For further work, this high-level investigation approach can also be implemented in other industries. This will enable both ESCOs and clients to investigate more potential energy saving projects at reduced risks and minimal resources.

5.2.3 Water systems

Background

Large quantities of water are used throughout the mining process for cooling, drilling and process purposes. Mismanagement of these water systems results in energy wastage in the form of oversupplied water. Dewatering systems consisting of large pumps are used to extract water from underground to surface. Reducing oversupply of water will decrease the energy required to transfer water between surface and underground.

Problem

The required data during investigations are not always readily available. Labour-intensive and time-consuming investigations are generally required to obtain the necessary data. During investigations, simpler methods are required to determine the potential scope for energy savings in the form of water supply.

Recommendation

In this study, 25 compressed air systems were used to develop a benchmark ERR. This benchmark method was used to evaluate potential savings using a simplified formula. It is recommended that further investigations should be conducted on the water usage of specific levels. These levels can be compared with the best practice water usage to identify potential scope. The water usage profiles on each level can be used to develop simplified benchmark models to identify potential scope.

5.2.4 Ventilation systems

Background

Ventilation systems are crucial for mining operations underground to extract harmful gases and cool underground working areas. Mismanagement of ventilation or extraction fans results in energy wastage. These fans use large amounts of energy and should be optimised according to demand. Operating these fans according to mining schedules will reduce unnecessary operation and electricity costs.

Problem

Complex multivariable simulations and calculations are required from skilled workers during conventional investigations to determine potential energy savings on ventilation and extraction fans. This process can be time-consuming and labour-intensive. During investigation phases, simpler methods are required to determine the scope of potential energy savings.

Recommendation

This study moved away from using multivariable inputs to determine possible savings on compressed air systems by developing a single variable approach that only requires power consumption as a single variable input. It is recommended that further investigations should be conducted on ventilation air demand patterns.

REFERENCES

[1] PricewaterhouseCoopers, “Highlighting trends in the South African mining industry,” vol. SA Mine, no. 8, pp. 1–10, 2016.

[2] K. Campnell, “Despite slower growth, China still key market for miners and Africa,” *Mining Weekly*, Johannesburg, 21-Apr-2017.

[3] I. Wormleighton, N. McKenna, D. Young, and P. Goldstein, “Bringing Industry Challenges to the Surface,” London, 2016.

[4] Chamber of Mines South Africa, “Facts and Figures,” Johannesburg, 2017.

[5] P. Mitchell, “Productivity in Mining: A Case for Broad Transformation,” United Kingdom, 2014.

[6] J. Vermeulen, “Cost effective management strategies for platinum mine cooling systems,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2015.

[7] R. Baxter, “PGMS in South Africa,” *Platinum Wage Negotiations*, 2014. [Online]. Available: http://www.platinumwagenegotiations.co.za/assets/downloads/fact-and-figures/platinum-state-of-the-nation.pdf. [Accessed: 30-Jan-2017].

[8] National Treasury, “Budget Review,” Pretoria, 2017.

[9] W. Schoeman, “A DSM approach for water usage and electricity costs on water distribution networks,” PhD Thesis, School of Electrical and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2016.

[10] W. Schoeman, A. Schutte, and M. Kleingeld, “The impact of reducing mine chilled water supply during periods of low production,” in *Proc. 11th Conf. Ind. Commer. Use Energy*, 2014, pp. 1–4.

[11] C. J. R. Kriel, “An alternative approach for sustainable industrial DSM in South Africa,” PhD Thesis, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2015.

[12] P. Maré, “Novel simulations for energy management of mine cooling systems,” PhD Thesis, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.

[13] B. Pascoe, H. J. Groenewald, and M. Kleingeld, “Improving mine compressed air network efficiency through demand and supply control,” in *Proc. 14th Conf. Ind. Commer. Use Energy*, 2017, pp. 1–5.

[14] Eskom, “Energy Advisory,” Johannesburg, 2017.

[15] J. P. De Jager, “Investigating the effect of pump availability on load shift performance,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2015.

[16] Eskom, “Eskom Demand Management Funding Models,” Johannesburg, 2011.

[17] J. H. Marais, “An integrated approach to optimise energy consumption of mine compressed air systems,” PhD Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2012.

[18] F. J. Ardakani and M. M. Ardehali, “Novel effects of demand side management data on accuracy of electrical energy consumption modeling and long-term forecasting,” *Energy Convers. Manag.*, vol. 78, pp. 745–752, 2014.

[19] B. Ngubane, C. Mabude, and V. Klein, “Eskom Integrated Report,” Johannesburg, 2015.

[20] Eskom, “Integrated Results for the year ended 31 March 2014,” 2014.

[21] R. Joubert, “Improved risk management processes for South African industrial ESCos,” Ph.D Thesis, School Development and Management, North-West University, Potchefstroom, South Africa, 2015.

[22] S. McMillan, “ESCO financing: An overview,” *Financ. Serv. Alert*, no. Dec, 2012.

[23] T. Shang, K. Zhang, P. Liu, Z. Chen, X. Li, and X. Wu, “What to allocate and how to allocate?-Benefit allocation in shared savings energy performance contracting projects,” *Energy*, vol. 91, pp. 60–71, 2015.

[24] S. Panev, N. Labanca, P. Bertoldi, T. Serrenho, C. Cahill, and B. B. Kiss, “ESCO market report for non-European countries 2013,” *JRC Sci. Policy Rep.*, pp. 12–18, 2014.

[25] A. Etzinger, “Systems engineering approach to Integrated Demand-side Management An Eskom case study,” *Electr. Control*, vol. September, no. September, 2014.

[26] M. Kleingeld, H. J. Groenewald, and J. F. Van Rensburg, “Practical problems experienced with industrial DSM projects,” in *Proc. 9th Conf. Ind. Commer. Use Energy*, 2012, pp. 1–6.

[27] H. Groenewald, “A performance-centered maintenance strategy for industrial DSM projects,” Ph.D Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2015.

[28] Eskom, “New ESCO DSM Model,” 2017. [Online]. Available: http://www.eskom.co.za/sites/idm/Business/Pages/Escobasisoffunding.aspx. [Accessed: 08-Jun-2017].

[29] SABS Standards Division, “SANS 50010:2011,” Pretoria, 2011.

[30] H. P. R. Joubert, M. A. L. Meek, and J. F. Van Rensburg, “A systems engineering approach to improve the M&V process of ESCos,” in *Proc. 11th Conf. Ind. Commer. Use Energy*, 2014.

[31] P. Lee, P. T. I. Lam, and W. L. Lee, “Risks in energy performance contracting (EPC) projects,” *Energy Build.*, vol. 92, pp. 116–127, 2015.

[32] D. de Canha, “Measurement and Verification Guideline: New ESCo Process Projects,” Johannesburg, 2015.

[33] L. F. van der Zee, “Modelling of electricity cost risks and opportunities in the gold mining industry,” PhD Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2014.

[34] IDC, “Developing a Vibrant ESCO Market -Prospects for South Africa’s Energy Efficiency future,” Johannesburg, 2013.

[35] F. C. Barnard and L. J. Grobler, “Baseline service level adjustment methodologies for energy efficiency projects on compressed air systems in the mining industry,” in *Proc. 9th Conf. Ind. Commer. Use Energy,* 2012, pp. 61–68.

[36] D. Struhs, “The Energy Efficiency Finance Network,” Eskom, Johannesburg, 2010.

[37] A. J. M. Van Tonder, “Automation of compressor networks through a dynamic control system,” PhD Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2014.

[38] M. Botha, “The state of the power system,” *Energize*, pp. 6–8, 2011.

[39] H. J. van Staden, J. I. G. Bredenkamp, and J. H. Marais, “Improving sustainability of previously implemented energy savings strategies on mine compressed air systems,” in *Proc. 14th Conf. Ind. Commer. Use Energy*, 2017, pp. 1–6.

[40] C. Cilliers, “Benchmarking electricity use of deep-level mines,” PhD Thesis, School Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.

[41] J. Bredenkamp, “Reconfiguring mining compressed air networks for cost savings,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2013.

[42] A. De Coning, “Sustained energy performance on compressed air systems for expanding gold mines,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2013.

[43] N. Steenkamp and V. Clark-Mostert, “Impact of illegal mining at historic gold mine locations, Giyani Greenstone Belt Area, South Africa,” in *9th Int. Mining History Congress*, 2012, p. 10.

[44] C. Cilliers, “Benchmarking electricity use of deep-level mine compressors,” in *Proc. 13th Conf. Ind. Commer. Use Energy*, 2016, pp. 1–6.

[45] D. Howett, “Compressed air— Higher pressure can equal lower cost,” *Energy Eng.*, vol. 100, no. 4, pp. 6–9, 2003.

[46] W. Chan, “Energy benchmarking in support of low carbon hotels: Developments, challenges, and approaches in China,” *Int. J. Hosp. Manag.*, vol. 31, no. 4, pp. 1130–1142, 2012.

[47] J. Keirstead, “Benchmarking urban energy efficiency in the UK,” *Energy Policy*, vol. 63, pp. 1–21, 2013.

[48] C. Filippín, “Benchmarking the energy efficiency and greenhouse gases emissions of school buildings in central Argentin,” *Build. Environ.*, vol. 35, no. 13, pp. 407–414, 2000.

[49] K. W. Mui, L. T. Wong, and L. Y. Law, “An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates,” *Appl. Energy*, vol. 84, no. 1, pp. 89–98, 2007.

[50] D. Gielen and P. Taylor, “Indicators for industrial energy efficiency in India,” *Energy*, vol. 34, no. 8, pp. 962–969, 2009.

[51] D. Phylipsen, K. Blok, E. Worrell, and J. De Beer, “Benchmarking the energy efficiency of Dutch industry: An assessment of the expected effect on energy consumption and CO2 emissions,” *Energy Policy*, vol. 30, no. 8, pp. 663–679, 2002.

[52] J. A. Curry, M. J. L. Ismay, and G. J. Jameson, “Mine operating costs and the potential impacts of energy and grinding,” *Miner. Eng.*, vol. 56, pp. 70–80, 2014.

[53] G. R. Ballantyne and M. S. Powell, “Benchmarking comminution energy consumption for the processing of copper and gold ores,” *Miner. Eng.*, vol. 65, no. 109–114, pp. 109–114, 2014.

[54] J. Oda, K. Akimoto, T. Tomoda, M. Nagashima, K. Wada, and F. Sano, “International comparisons of energy efficiency in power, steel, and cement industries,” *Energy Policy*, vol. 44, pp. 118–129, 2012.

[55] D. Y. L. Chan, C. F. Huang, W. C. Lin, and G. B. Hong, “Energy efficiency benchmarking of energy-intensive industries in Taiwan,” *Energy Convers. Manag.*, vol. 77, pp. 216–220, 2014.

[56] D. Saygin, E. Worrell, M. K. Patel, and D. J. Gielen, “Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries,” *Energy*, vol. 36, no. 11, pp. 6661–6673, 2011.

[57] J. Ke, L. Price, M. McNeil, N. Z. Khanna, and N. Zhou, “Analysis and practices of energy benchmarking for industry from the perspective of systems engineering,” *Energy*, vol. 54, pp. 32–44, 2013.

[58] J. Tshisekedi, “Energy consumption standards and costs in the South African mining industry,” M.Eng, Engineering and the Built Environment,University of the Witwatersrand, 2007.

[59] J. W. Lodewyckx, “Investigating the effects of different DSM strategies on a compressed air ring,” in *Proc. 4th Conf. Ind. Commer. Use Energy*, 2007, pp. 1–3.

[60] D. Mckay, “Section 54s cost SA mines R4.8bn in 2015, and 2016 may be worse,” *Miningm*, 2016. [Online]. Available: http://www.miningmx.com/opinion/columnists/27866-stoppages-lop-r4-8bn-off-2015-revenue-2016-worse/. [Accessed: 06-Apr-2017].

[61] J. L. M. Felix, S. A. Dominguez, L. R. Rodriguez, J. M. S. Lissen, J. S. Ramos, and F. J. S. de la Flor, “ME3A: Software tool for the identification of energy saving measures in existing buildings: Automated identification of saving measures for buildings using measured energy consumptions,” in *2016 IEEE 16th Int. Conf. on Environ. and Elect. Eng.(EEEIC)*, 2016, pp. 1–6.

[62] L. Pérez-Lombard, J. Ortiz, R. González, and I. R. Maestre, “A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes,” *Energy Build.*, vol. 41, no. 3, pp. 272–278, 2009.

[63] C. Yan, S. Wang, and F. Xiao, “A simplified energy performance assessment method for existing buildings based on energy bill disaggregation,” *Energy Build.*, vol. 55, pp. 563–574, 2012.

[64] V. Peyramalea and C. Wetzel, “Analyzing the energy-saving potential of buildings for sustainable sefurbishment,” *Procedia Environ. Sci.*, vol. 38, pp. 162 – 168, 2017.

[65] HM Government, “Department for Environment, Food & Rural Affairs,” 2008. [Online]. Available: https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs. [Accessed: 13-Feb-2017].

[66] A. M. A. Mohamed, A. Al-Habaibeh, H. Abdo, and S. Elabar, “Towards exporting renewable energy from MENA region to Europe: An investigation into domestic energy use and householders’ energy behaviour in Libya,” *Appl. Energy*, vol. 146, pp. 247–262, 2015.

[67] D. M. Murray, J. Liao, L. Stankovic, and V. Stankovic, “Understanding usage patterns of electric kettle and energy saving potential,” *Appl. Energy*, vol. 171, pp. 231–242, 2016.

[68] R. Saidur, N. A. Rahim, and M. Hasanuzzaman, “A review on compressed-air energy use and energy savings,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 4, pp. 1135–1153, 2010.

[69] R. Saidur, N. A. Rahim, H. H. Masjuki, S. Mekhilef, H. W. Ping, and M. F. Jamaluddin, “End-use energy analysis in the Malaysian industrial sector,” *Energy*, vol. 34, no. 2, pp. 153–158, 2009.

[70] K. Matsuda, “Comparative study of energy saving potential for heavy chemical complex by area-wide approach,” *Energy*, vol. 116, pp. 1397–1402, 2015.

[71] K. Matsuda, Y. Hirochi, H. Tatsumi, and T. Shire, “Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants,” *Energy*, vol. 34, no. 10, pp. 1687–1692, 2009.

[72] C. Loredo, N. Roqueni, and A. Ordonez, “Modelling flow and heat transfer in flooded mines for geothermal energy use: A review,” *Int. J. Coal Geol.*, vol. 164, pp. 115–122, 2016.

[73] P. Maré, J. I. G. Bredenkamp, and J. H. Marais, “Evaluating compressed air operational improvements on a deep - level mine through simulations,” in *Proc. 14th Conf. Ind. Commer. Use Energy,* 2017, pp. 1–8.

[74] J. A. Snyman, “Integrating various energy saving initiatives on compressed air systems of typical South African gold mines,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2011.

[75] C. Scheepers, “Implementing energy efficiency measures on the compressed air network of old South African mines,” M.Eng Dissertation, School of Electrical and Electronic Engineering, North-West University, Potchefstroom, South Africa, 2011.

[76] L. Liebenberg, D. Velleman, and W. Booysen, “A simple demand-side management solution for a typical compressed-air system at a South African gold mine,” *J. Energy South. Africa*, vol. 23, no. 2, pp. 20–29, 2012.

[77] W. Booysen and J. F. Van Rensburg, “Management on closed loop underground fridge plants and the effects on working conditions,” in *Proc. 10th Conf. Ind. Commer. Use Energy*, 2013, pp. 1–4.

[78] W. Booysen, “Reducing energy consumption on RSA mines through optimised compressor control,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2010.

[79] J. N. Du Plessis and R. Pelzer, “Development of an intelligent control system for mine compressor systems,” in *Proc. 8th Conf. Ind. Commer. Use Energy*, 2011, pp. 59–63.

[80] J. N. Du Plessis, “Development of an energy management solution for mine compressor systems,” M.Eng Dissertation, School of Computer and Electronical Engineering, North-West University, Potchefstroom, 2011.

[81] C. J. R. Kriel, “Modernising underground compressed air DSM projects to reduce operating costs,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2013.

[82] K. Brun and M. G. Nored, “Application guideline for centrifugal compressor surge control systems,” *Appl. Guidel. Centrif. Compress. surge Control Syst.*, vol. 4.3, no. April, pp. 9–10, 2008.

[83] J. Vermeulen, C. Cilliers, and J. H. Marais, “Cost-effective compressor control to reduce oversupply of compressed air,” *Proc. 14th Conf. Ind. Commer. Use Energy*, pp. 1–6, 2017.

[84] J. Jonker, H. P. R. Joubert, and H. G. Brand, “Dynamic control on compressed air supply for sustainable energy savings,” in *Proc. 14th Conf. Ind. Commer. Use Energy*, 2017, pp. 1–6.

[85] E. Condron IV, “Cost savings realized through proper sizing of an excessive instrument air system,” M.Sc Dessertation, University of North Texas, United States of America, 2003.

[86] C. J. R. Kriel, J. H. Marais, and M. Kleingeld, “Modernising underground compressed air DSM projects to reduce operating costs,” in *Proc. 11th Conf. Ind. Commer. Use Energy*, 2014.

[87] R. Joubert, “Cost and time effective DSM on mine compressed air systems,” M.Eng Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2010.

[88] A. Garbers, M. Kleingeld, and J. Van Rensburg, “Energy savings through auto compression and the air distribution control of a deep level gold mine,” *Proc. 7th Conf. Ind. Commer. Use Energy*, 2010.

[89] H. P. R. Joubert, G. Bolt, and J. F. Van Rensburg, “Energy savings on mining compressed air networks through dedicated process plant compressors,” *Proc. 9th Conf. Ind. Commer. Use Energy*, pp. 99–102, 2012.

APPENDIX A : SIMULATION RESULTS FOR VERIFICATION OF CONTRIBUTION 1

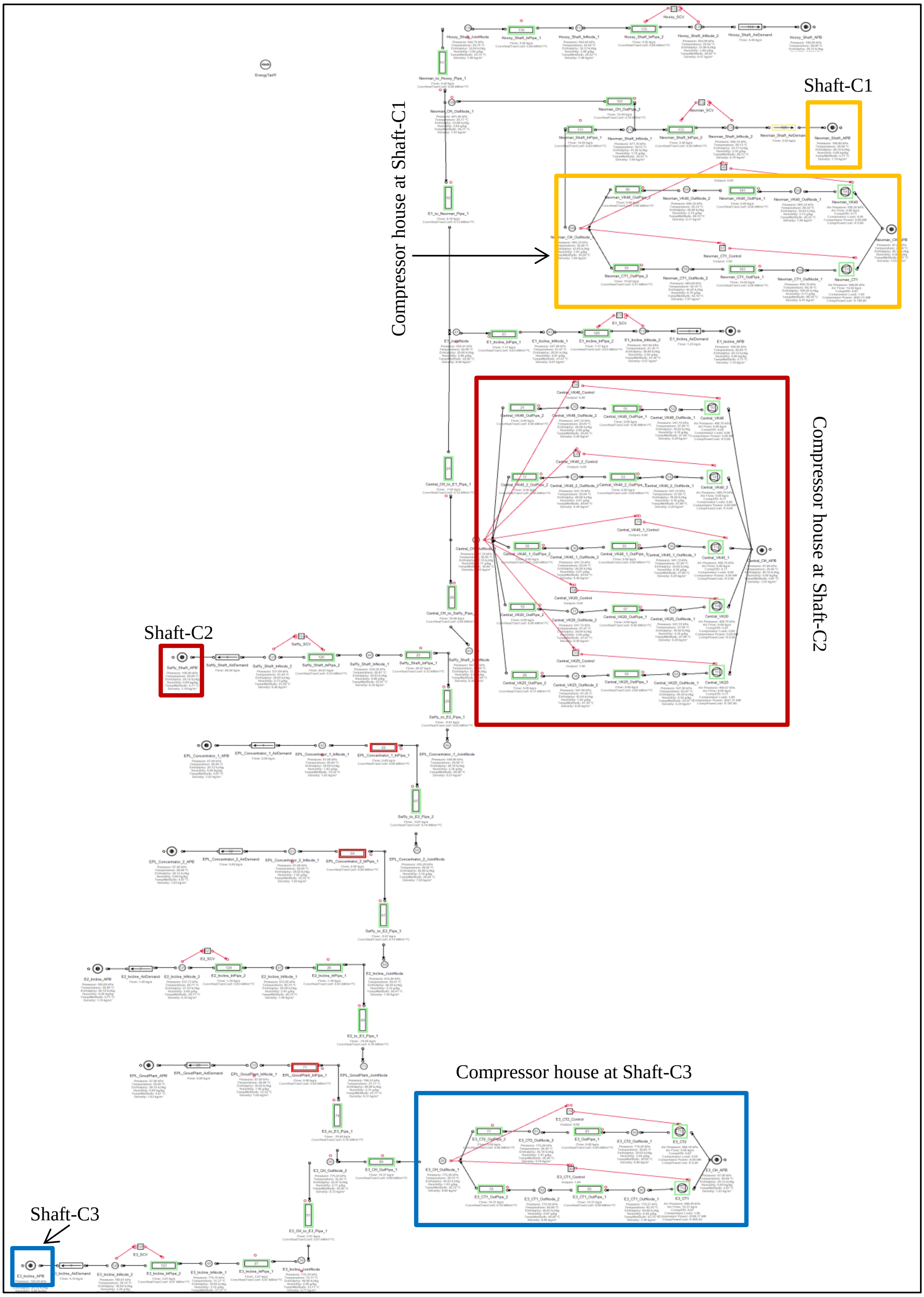


Figure 64: Simulation layout of verification study in Section 3.5.2

Table 33: Pressure consumption data input for simulation model

TIME	BASELINE PRESSURE [kPa]	SCENARIO 1 PRESSURE (BEST PRACTICE) [kPa]	SCENARIO 2 PRESSURE (POOR PRACTICE) [kPa]	TIME	BASELINE PRESSURE [kPa]	SCENARIO 1 PRESSURE (BEST PRACTICE) [kPa]	SCENARIO 2 PRESSURE (POOR PRACTICE) [kPa]
0:00	461	251	598	12:00	590	590	590
0:30	461	252	598	12:30	596	596	596
1:00	461	252	598	13:00	586	583	573
1:30	461	252	598	13:30	545	335	598
2:00	458	250	598	14:00	538	346	598
2:30	459	251	598	14:30	478	341	598
3:00	494	275	598	15:00	481	297	598
3:30	497	277	598	15:30	454	286	598
4:00	507	283	598	16:00	464	297	598
4:30	504	281	598	16:30	444	224	598
5:00	519	293	598	17:00	460	232	598
5:30	566	399	598	17:30	437	217	598
6:00	524	525	551	18:00	436	215	598
6:30	577	575	576	18:30	410	200	598
7:00	576	576	575	19:00	397	192	598
7:30	571	571	570	19:30	414	201	598
8:00	597	593	598	20:00	462	278	598
8:30	608	610	608	20:30	453	249	598
9:00	572	567	586	21:00	459	254	598
9:30	574	574	598	21:30	465	256	598
10:00	611	612	612	22:00	481	267	598
10:30	618	618	618	22:30	481	265	598
11:00	612	612	612	23:00	475	261	598
11:30	602	602	602	23:30	469	257	598

Table 34: Simulated power consumption data and results

TIME	BASELINE POWER [KW]	SCENARIO 1 POWER (BEST PRACTICE) [KW]	SCENARIO 2 POWER (POOR PRACTICE) [KW]	TIME	BASELINE POWER [KW]	SCENARIO 1 POWER (BEST PRACTICE) [KW]	SCENARIO 2 POWER (POOR PRACTICE) [KW]
0:00	11124	5664	17571	12:00	19565	19227	19179
0:30	11691	5666	17452	12:30	18451	17686	18742
1:00	11694	5668	17373	13:00	17701	16924	18221
1:30	11717	5669	17302	13:30	15371	8865	17788
2:00	11745	5667	17328	14:00	14473	7886	17992
2:30	11756	5669	17366	14:30	13016	7848	18977
3:00	12102	5710	17453	15:00	12991	6760	18672
3:30	12093	5711	17469	15:30	12748	6613	19181
4:00	11994	5720	17356	16:00	12746	6647	19057
4:30	11965	5714	17513	16:30	10899	4726	17660
5:00	12382	5731	17077	17:00	9257	4505	17704
5:30	13024	7964	17828	17:30	9368	4508	18287
6:00	13097	12608	16914	18:00	9836	4510	18059
6:30	14280	13712	17101	18:30	9899	4509	18532
7:00	14006	14306	17227	19:00	10099	4506	18703
7:30	14107	14210	17300	19:30	11048	4500	17985
8:00	15492	14413	17954	20:00	11172	5580	17685
8:30	16873	16945	18089	20:30	11129	5657	18085
9:00	17928	17225	18274	21:00	11531	5674	17956
9:30	19918	17313	18534	21:30	11351	5680	17862
10:00	21633	20226	20139	22:00	11305	5699	17416
10:30	22611	20559	20535	22:30	11274	5693	17265
11:00	22141	20438	20415	23:00	11224	5684	17456
11:30	21153	20146	20134	23:30	11206	5675	17568

APPENDIX B : POWER BASELINE DATA

Table 35: Compressed air system power baseline data collected for Case Study 1

TIME	BASELINE POWER CONSUMPTION [MW]	TIME	BASELINE POWER CONSUMPTION [MW]
0:00	13.50	12:00	16.50
0:30	13.50	12:30	16.30
1:00	13.40	13:00	16.40
1:30	13.50	13:30	15.60
2:00	13.50	14:00	14.50
2:30	13.60	14:30	13.80
3:00	13.50	15:00	13.50
3:30	13.60	15:30	13.40
4:00	13.70	16:00	13.20
4:30	13.70	16:30	13.20
5:00	13.70	17:00	13.20
5:30	13.90	17:30	13.30
6:00	13.90	18:00	13.30
6:30	13.80	18:30	13.40
7:00	13.80	19:00	13.40
7:30	13.80	19:30	13.40
8:00	13.90	20:00	13.10
8:30	13.90	20:30	13.30
9:00	13.80	21:00	13.60
9:30	14.00	21:30	13.70
10:00	13.90	22:00	13.60
10:30	14.20	22:30	13.60
11:00	14.60	23:00	13.60
11:30	15.70	23:30	13.60

Table 36: Compressed air system power baseline data collected for Case Study 2

TIME	BASELINE POWER CONSUMPTION [MW]	TIME	BASELINE POWER CONSUMPTION [MW]
0:00	16.96	12:00	22.01
0:30	16.93	12:30	21.56
1:00	16.87	13:00	20.53
1:30	16.84	13:30	18.50
2:00	16.53	14:00	16.84
2:30	16.30	14:30	16.04
3:00	16.13	15:00	16.20
3:30	16.07	15:30	16.28
4:00	16.07	16:00	16.00
4:30	16.51	16:30	15.29
5:00	16.55	17:00	14.78
5:30	17.00	17:30	14.88
6:00	18.69	18:00	15.82
6:30	20.49	18:30	16.88
7:00	21.70	19:00	16.91
7:30	22.63	19:30	16.89
8:00	23.53	20:00	17.01
8:30	24.03	20:30	17.07
9:00	24.32	21:00	17.04
9:30	24.55	21:30	16.98
10:00	24.37	22:00	16.90
10:30	23.94	22:30	16.88
11:00	23.20	23:00	16.85
11:30	22.48	23:30	16.74

APPENDIX C : INTEGRATED APPROACH

Load clipping strategy test in Case Study 1

Power consumption results of load clipping test on Compressor-5

After implementing the load clipping test, the power consumption profile was compared with the baseline power consumption before the test. The result is shown in Figure 65. During the test, an average energy saving of 2 308 kWh was achieved. Thus, the Eskom target was achieved. However, more potential savings exist if the compressed air demand could be reduced during Eskom's evening peak period. This will also extend the duration that a compressor can be stopped during Eskom's evening peak periods.

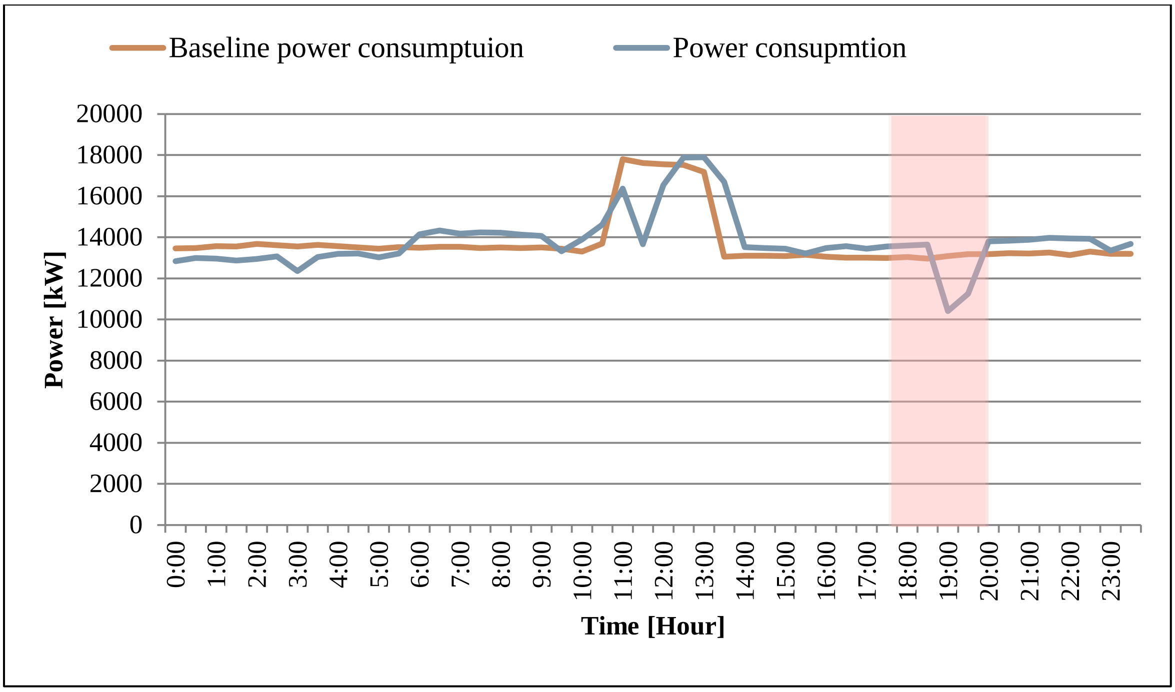


Figure 65: Baseline power consumption compared with load clipping test result

Pressure and flow demand results of load clipping test on Compressor-5

During the test, the compressed air supply reduced from 84 671 m^3/h to 65 455 m^3/h by stopping Compressor-5 within the peak drilling shift. During the load clipping test, the system pressure reduced from 596 kPa to 518 kPa. When the pressure decreased below the minimal limit, Compressor-5 was started to recover the system pressure to above the low limit of 520 kPa (see Figure 66).

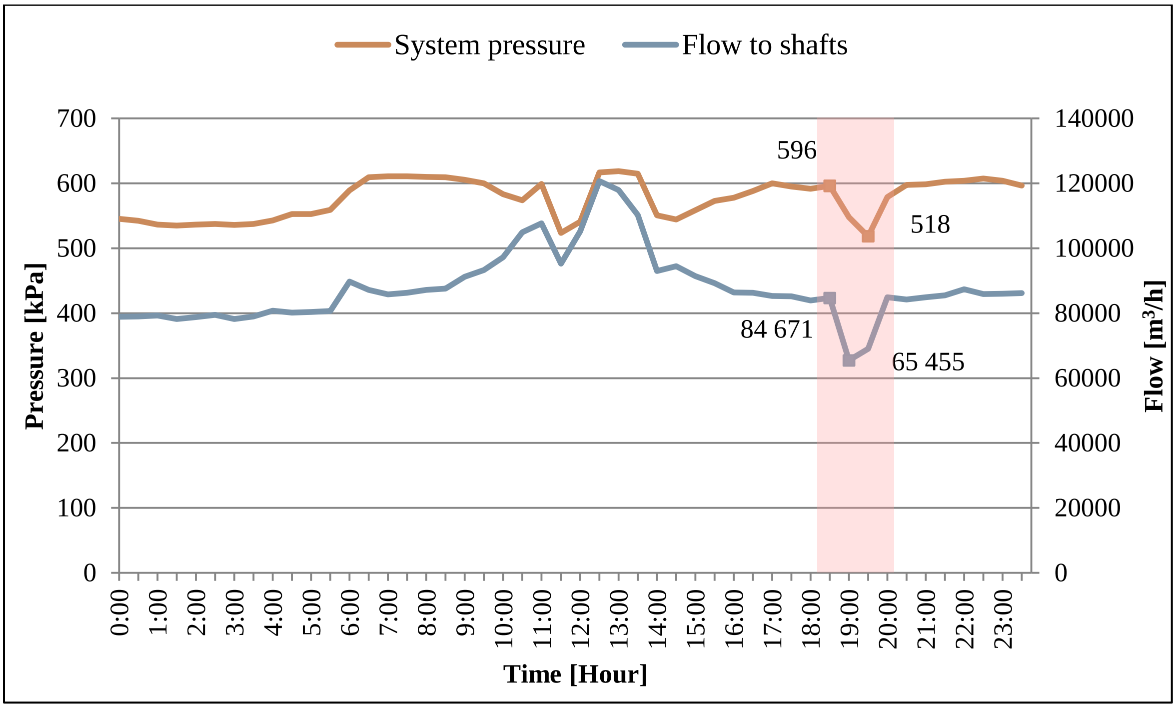


Figure 66: Load clipping test impact on pressure and flow profiles during Case Study 1

Guide vane position during load clipping test on Compressor-5

The guide vane position of Compressor-5 between 19:00 and 20:00 indicates that Compressor-5 was stopped (see Figure 67). The system pressure recovered within a half-hour from starting Compressor-5. As a result, the guide vane position of Compressor-5 was at the minimum position for the remainder of the evening shift.

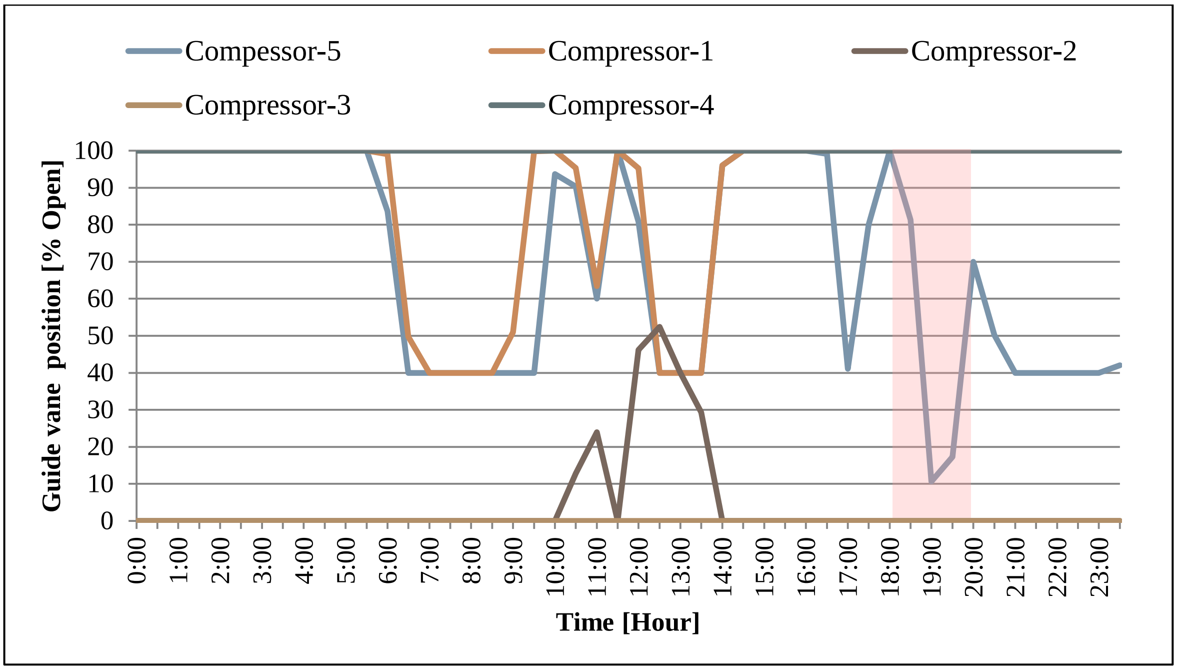


Figure 67: Load clipping test impact on guide positions during Case Study 1

Blow-off position during load clipping test on Compressor-5

The blow-off position of Compressor-5 was fully open while stopped (see Figure 68). After starting Compressor-5 due to low pressures, the compressor was under full load for a half-hour until the system pressure set point was reached. The compressor was in a blow-off state for the remainder of the evening shift due to oversupply.

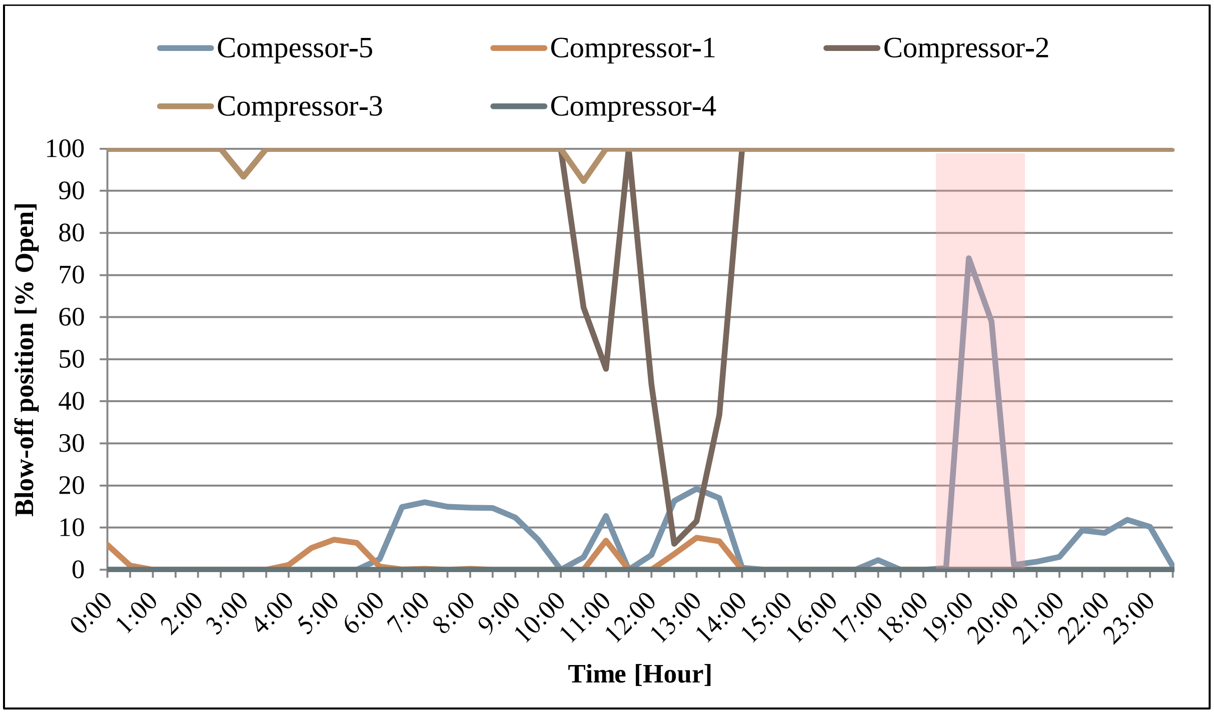


Figure 68: Load clipping test impact on blow-off positions during Case Study 1

Conclusion of load clipping test

By evaluating the results of the tests conducted, it was learned that the variables required to evaluate the impact of strategies are power consumption, system pressure, blow-off valve position and guide vane angle. The system pressure cannot be sustained with one fewer compressor operating during the evening shift. However, by stopping Compressor-5, the system pressure low limit was reached within 49 minutes. The required pressure and flow supply cannot be sustained for longer periods due to demand during this time.

Together with mine management, a leakage audit was initiated after the load clipping test. By reducing the unwanted flow demand (leaks/open ends), the system pressure could be sustained for longer periods during a load clipping strategy.

Leak repairs in Case Study 1

Overview

A leakage audit was conducted to indicate areas that needed urgent attention. By repairing air leaks, the compressed air demand would decrease. Thus, if sufficient air leaks could be stopped, the load clipping initiatives would achieve more savings than during the test constructed in Section 4.3.2. This section shows some of the findings during the audit, which contributed to the unwanted air demand.

Leak repair on surface

Various leaks on the surface were identified and repaired. Most of the compressed air network was found to be neglected and poorly installed. Figure 69 shows how the compressed air network on the surface was exposed to the risk created by adverse climates.

Figure 69: Pipeline of compressed air system connecting main shafts and compressors

Pipe support

It was found that old pipe sections were used as support for the compressed air pipe network. These old pipe sections collapsed in some cases as shown in Figure 70. The improper pipe support added additional stresses on the joints of the pipe network.

Figure 70: Collapsed pipe support in Case Study 1

Properly concreted supports were recommended to replace the poor pipe support methods previously used. Figure 71 illustrates the recommended supports.

Figure 71: Concrete pipe support for reliable support

Pipe joint connections

The pipe network in Case Study 1 used two types of joints namely, Victaulic joints and flange joints. The Victaulic joints shown in Figure 72 are more vulnerable to leaks when the pipeline shifts due to unstable gravel or collapsing pipe supports. Adverse climate conditions, including the rainy season, add to the movement in the supports. Most of the leaks found on the surface were at the joints of the pipe sections.

Figure 72: Victaulic joints connecting pipes in Case Study 1

Figure 73 shows an example where two pipe sections were joined. An assumption was made that the pipe section installed was not measured properly. Thus, the sections were too short and could not be joined and sealed properly. As a result, compressed air escaped through the connections.

Figure 73: Poor pipe connection on the compressed air network of Case Study 1

The leak in Figure 74 was repaired by extending one of the sections. Figure 77 shows the improved connection between two pipe sections. This allowed the joints to be connected as expected to prevent compressed air leaking through the flange joints.

Figure 74: Repaired flange connection on the compressed air pipe network of Case Study 1

Expansion joints

The audit revealed that expansion joints also contribute to leaks on the surface (see Figure 75). The poor pipe support highlighted in Case Study 1 contributes to the leaks found on the expansion joints. These joints are installed to accommodate the expansion and contraction of pipes due to adverse climate conditions.

Figure 75: Impact of temperature change on the compressed air pipe network in Case Study 1

Figure 76 shows a newly installed expansion joint. The malfunctioning expansion joints were improved by replacing the poor pipe support with the recommended concrete supports.

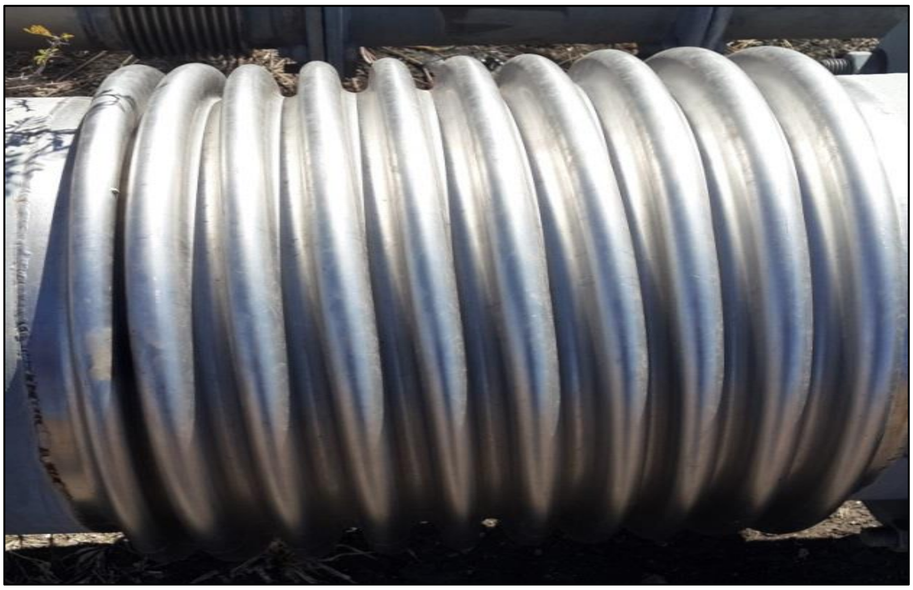


Figure 76: New expansion joint installed on the compressed air pipe network of Case Study 1

Isolation points

One of the largest contributors to leaks on compressed air pipe networks is insufficient isolation from decommissioned end users. Figure 87 shows a decommissioned valve on the compressed air pipe network of Case Study 1 that had not been isolated sufficiently. This caused significant air leaks through the valve. Figure 78 shows a pipe end that had previously supplied air to workshops. The pipe end also leaked due to insufficient isolation. Figure 79 shows another poor method previously used to repair an air leak in Case Study 1.

Figure 77: Decommissioned valve

Figure 78: Pipe end that previously supplied air to workshops

Figure 79: Improper leak repair method on the compressed air pipe network of Case Study 1

Leak repair underground

Due to safety and security concerns, the mine of Case Study 1 did not allow pictures to be taken during the audit for underground leaks. However, the leaks underground were similar to the leaks on the surface. At Shaft-S from Case Study 1, 26-level was closed down. Thus, no mining operations took place at 26-level. However, the pipe network that previously supplied air for mining operations was not isolated (open-end) and increased the air demand by an estimated 20 000 m^3/h.

Summary of leak repair for Case Study 1

After conducting a leakage audit on the surface and underground, mine management was motivated to further improve the compressed air optimisation; therefore, they instructed mine personnel to repair all identified leaks. The leak repair took an estimated 39 days of constant investigations and repairs. It was determined that 25 000 m^3/h of leaks were repaired. Most of these leaks were found underground.

Energy saving strategies implemented after leak repairs

Overview

The combination of existing oversupply before the leak repairs and the reduction of unwanted air demand due to air leaks enabled the mine of Case Study 1 to operate one fewer compressor during a normal production day. The reduced air demand also introduced opportunities to operate different compressor combinations.

Stop compressor

It was determined that Compressor-1 was the least effective compressor and should be stopped to reduce the oversupply of compressed air.

Improve compressor selection

Compressor-1 was previously operated as a baseload compressor in combination with Compressor-4 and Compressor-5. Compressor-2 operated as trimming compressor during the drilling shift. However, it was determined that Compressor-2 was the most efficient compressor and should be operated as a baseload compressor.

Compressor-5 experienced blow-off more frequently than other compressors. It was concluded that this compressor was the most reliable to be stopped and started. Therefore, Compressor-5 could operate as the trimming compressor. As a result, Compressor-5 experienced less blow-off than during original operations. However, although the blow-off was reduced, oversupply still occurred when Compressor-5 operated as a trimming compressor during drilling shifts.

Impact of leak repair and improved compressor combination on compressed air oversupply

Although one baseload compressor was stopped after major leak repairs and the compressor combinations were improved, an oversupply of compressed air still occurred. Figure 80 shows how the oversupply reduced significantly due to the Compressor-5 only operating during the drilling shift. However, the blow-off valve still released oversupplied compressed air into the atmosphere. Therefore, a need existed to reduce the oversupply further [83].

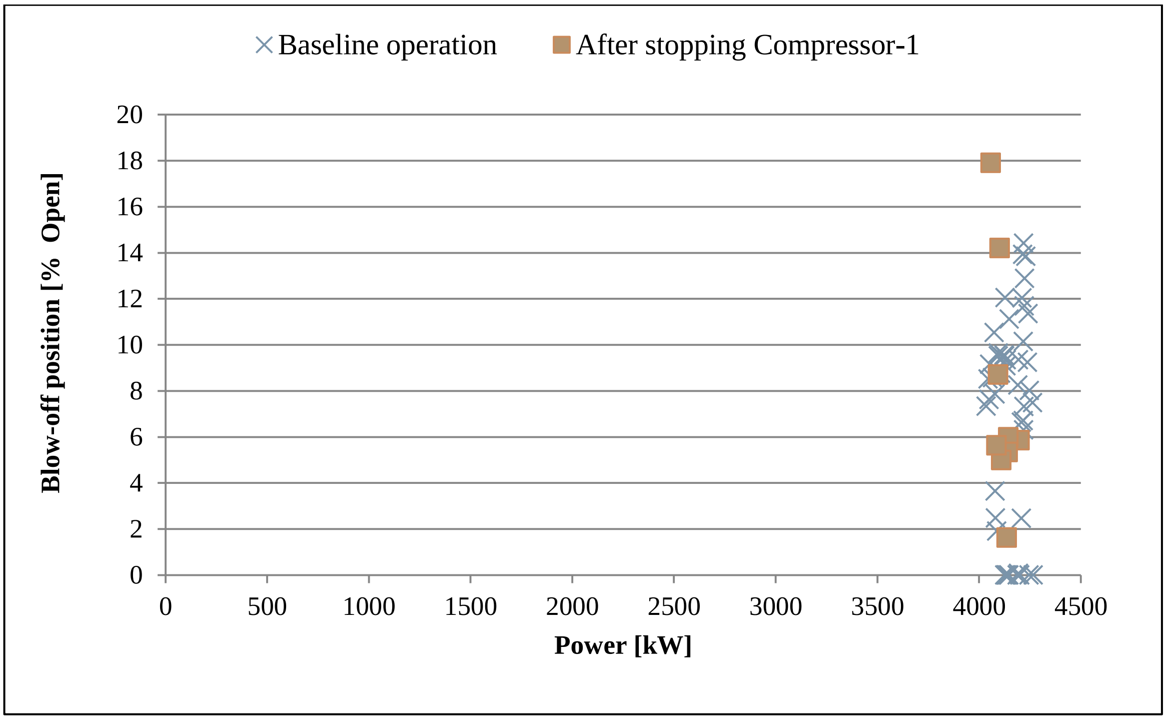


Figure 80: Impact of new compressor combination on the oversupply of Compressor-5 [83]

Figure 81 shows the impact of the new compressor combination on the delivery flow of Compressor-5. It was noted that Compressor-5 could only reduce the discharge flow to a minimum of 19 000 m^3/h with the existing throttle control through the guide vanes. At minimal load, no significant power reduction is achieved compared with full load. Therefore, a need existed to further reduce the discharge flow, and realise energy savings at minimal load or during blow-off conditions.

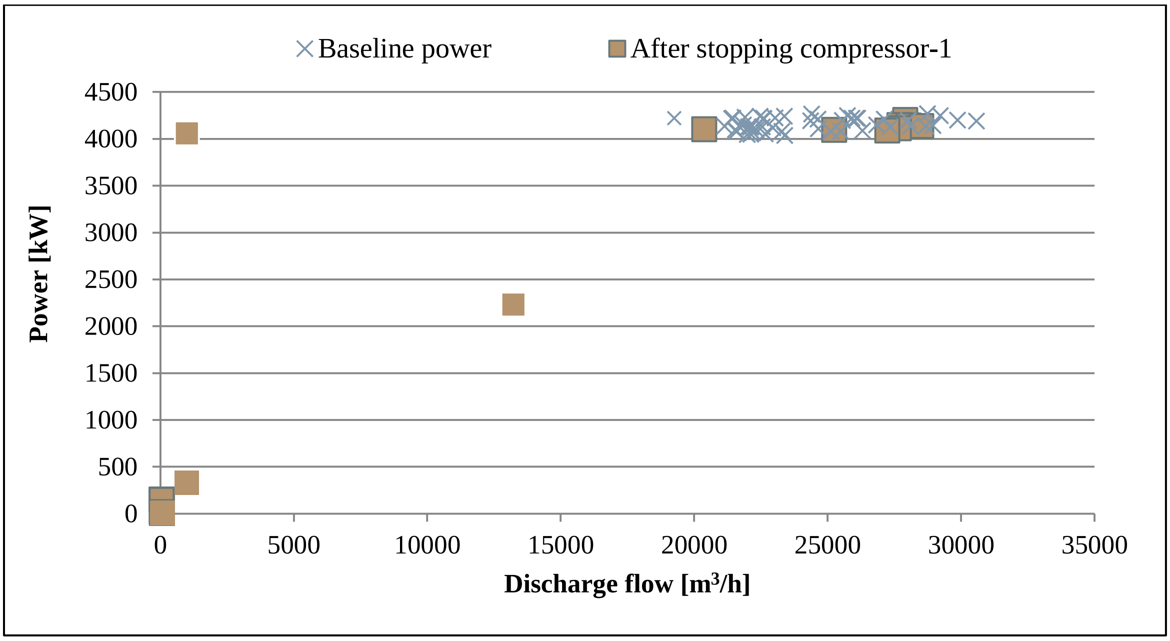


Figure 81: Limited throttle control of Compressor-5 in Case Study 1 [83]

Cost-effective throttle control to reduce oversupply

Overview

Vermeulen et al. developed a cost-effective solution for reducing the oversupply on Compressor-5 further. Figure 82 shows the actual Compressor-5 used in Case Study 1. The compressor has a bottom and a top level. The inlet airflow is sucked from the atmosphere, and passes through an existing butterfly valve located at the bottom level. The air then passes through the compressor to be compressed and is ultimately discharged into the compressed air network [83].

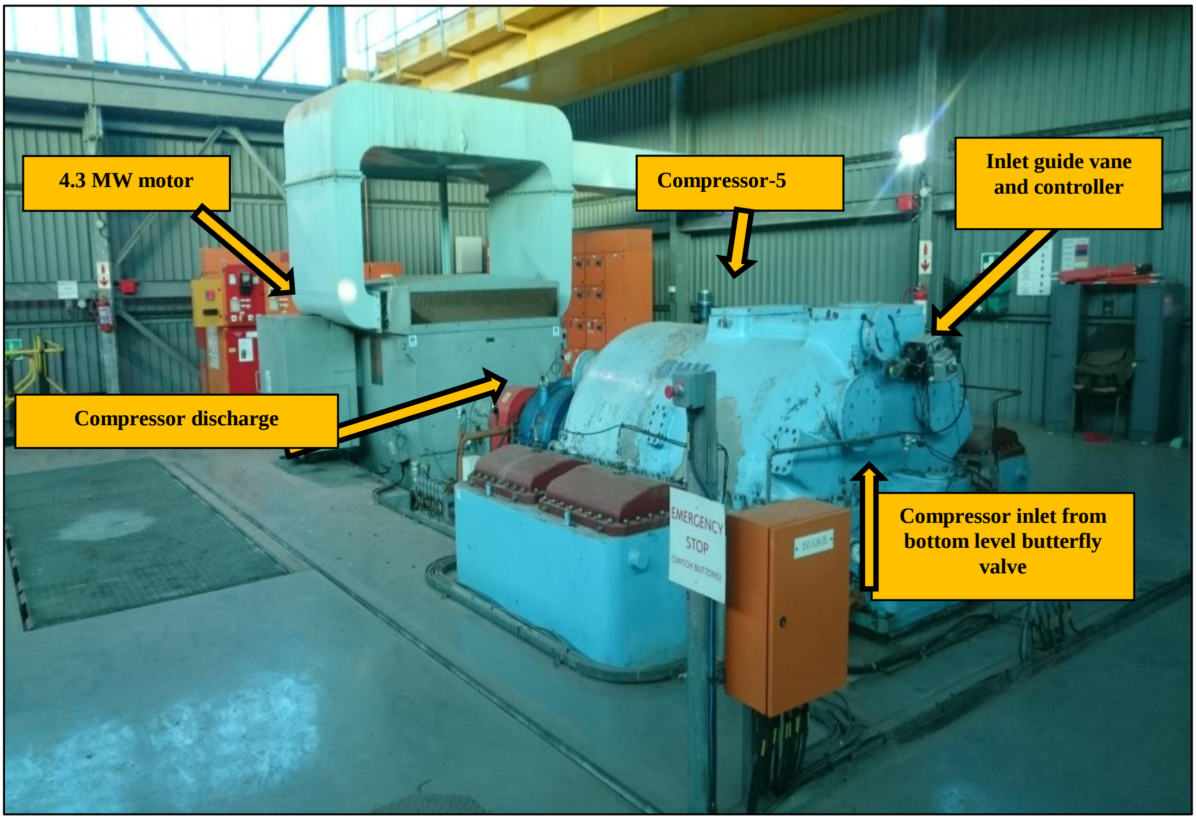


Figure 82: Compressor-5 in Case Study 1

Figure 83 shows the actual butterfly valve located at the bottom level of the compressor. This butterfly valve was originally used to isolate the suction from the atmosphere. The butterfly valve could only be manually opened and closed via an actuator connected to a mechanical arm.

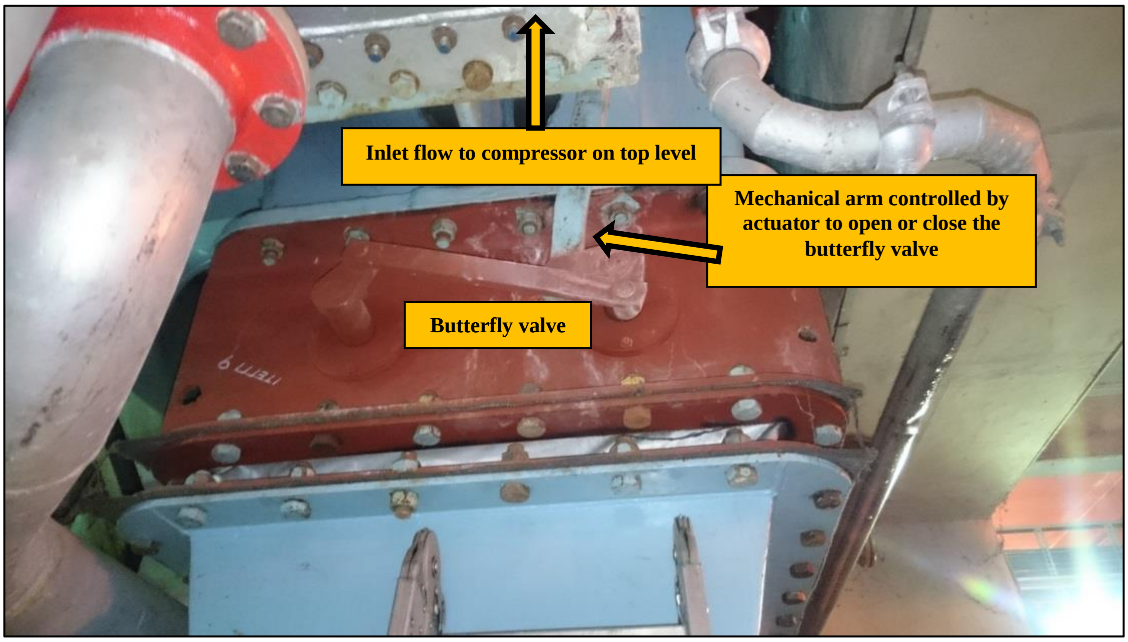


Figure 83: Existing manual butterfly valve to allow air through Compressor-5

Original compressor control and limitations

The original control of Compressor-5 is illustrated in Figure 84. The existing guide vane control of Compressor-5 only reduced the discharge flow to a minimum of 19 000 m^3/h to reduce the oversupplied compressed air. When oversupply persists after the guide vane reached minimum angle, the blow-off valve opens to eject the oversupply into the atmosphere. Therefore, a need existed to reduce the oversupplied discharge air further. This could result in lower generation cost for compressed air. However, due to mechanical constraints, it was not feasible to improve the existing guide vane control itself.

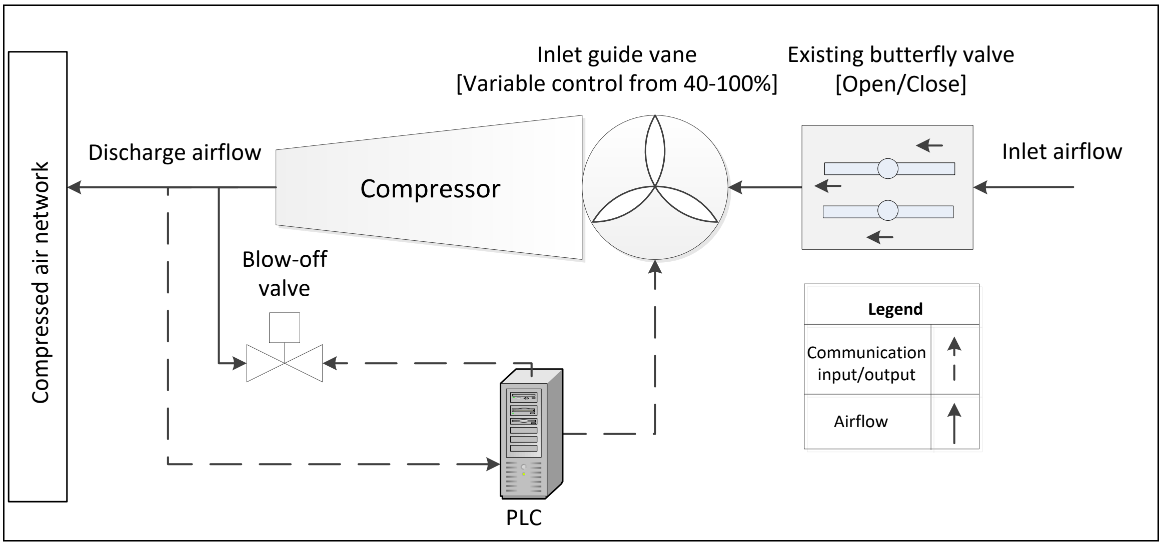


Figure 84: Original control of Compressor-5 with limited guide vane throttle control

New cost-effective compressor control

Vermeulen et al. implemented an actuator on the existing butterfly valve (see Figure 85). This enabled improved throttle control to further reduce airflow through the compressor. The variable control on the guide vane was decommissioned (see Figure 86) while the guide vane was fixed at a 100% open position. This implementation was an estimated R0.2 million. Conventional methods for improving guide vane control are an estimated R2 million.

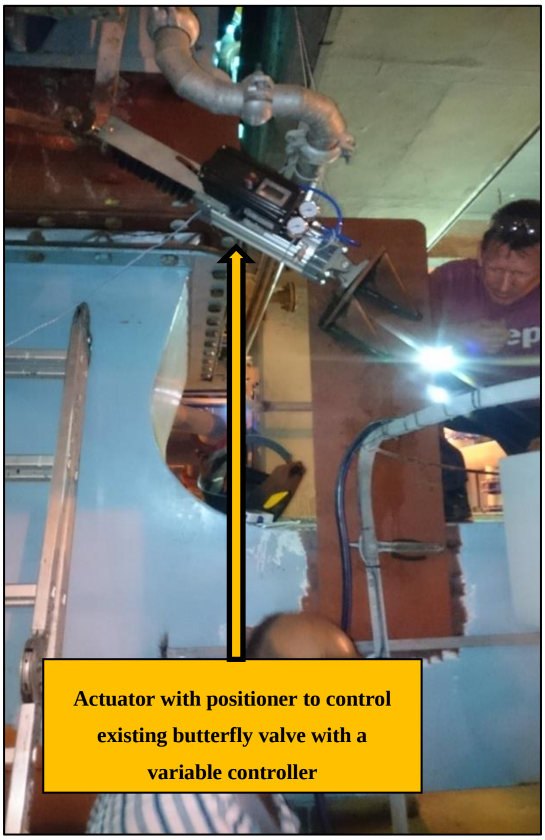


Figure 85: Installing an actuator on an existing butterfly valve for improved throttle control

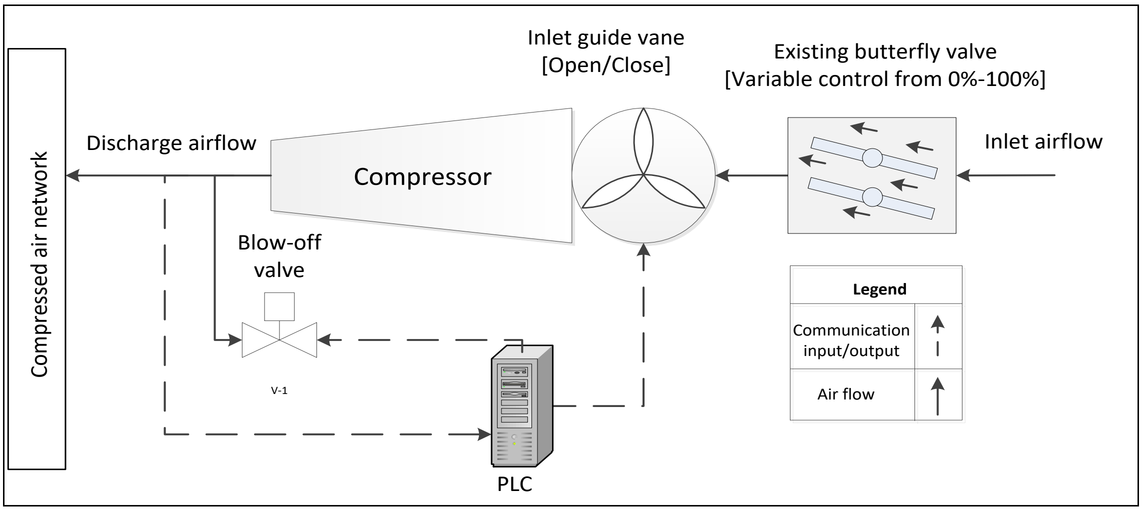


Figure 86: Improved throttle control to further reduce the flow through the compressor [83]

This new control combined existing control strategies with available infrastructure to further reduce flow through the compressor. The impact of the new control on the discharge flow is shown in Figure 87. The new control enabled Compressor-5 to further reduce the flow from 19 000 m^3/h to 15 000 m^3/h. As a result, an average saving of 650 kWh was realised. Figure 88 shows the impact that the improved throttle control had on the guide vane angle and power consumption.

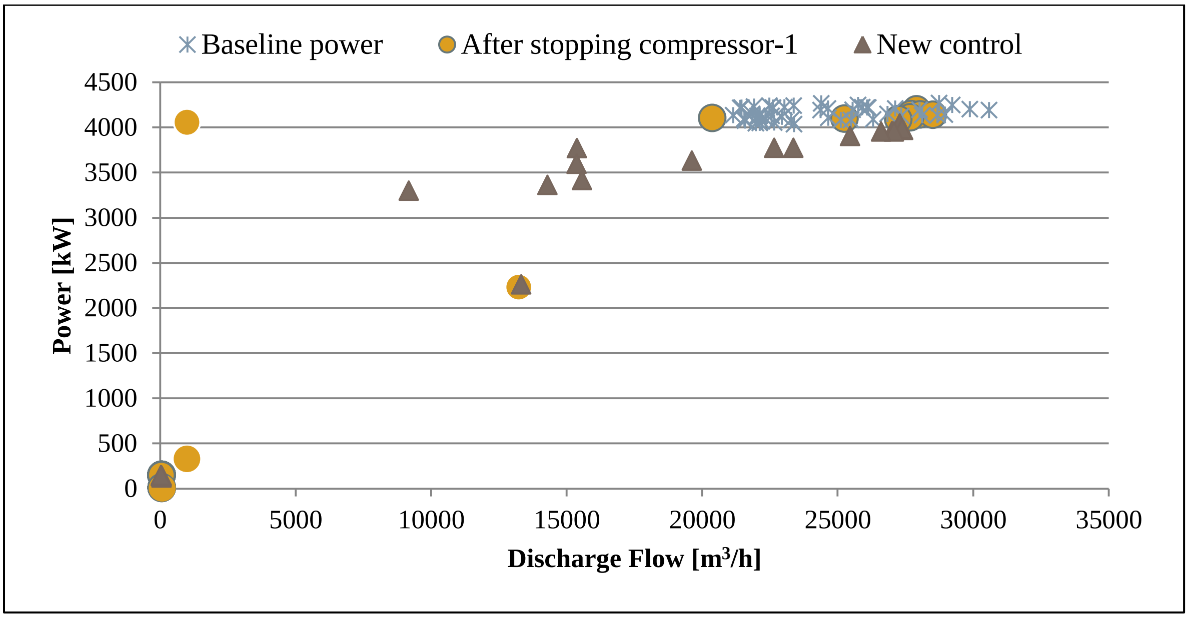


Figure 87: New control further reduce the discharge flow during oversupply

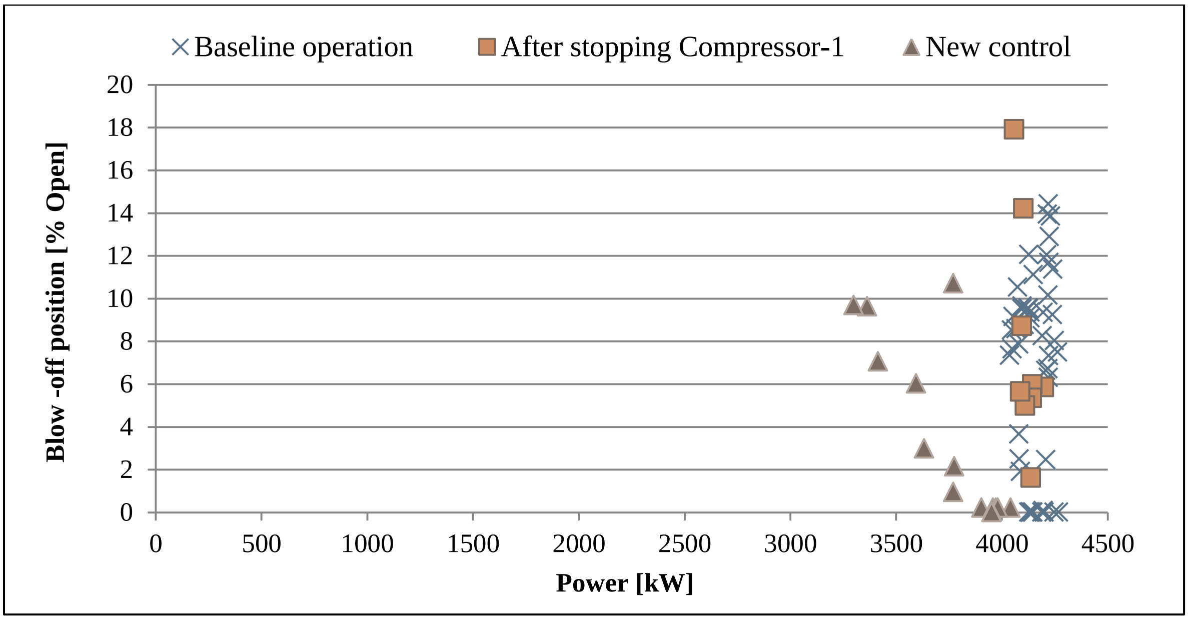


Figure 88: Impact of new improved throttle control during blow-off conditions

APPENDIX D : SIMULATION MODEL OF CASE STUDY 2

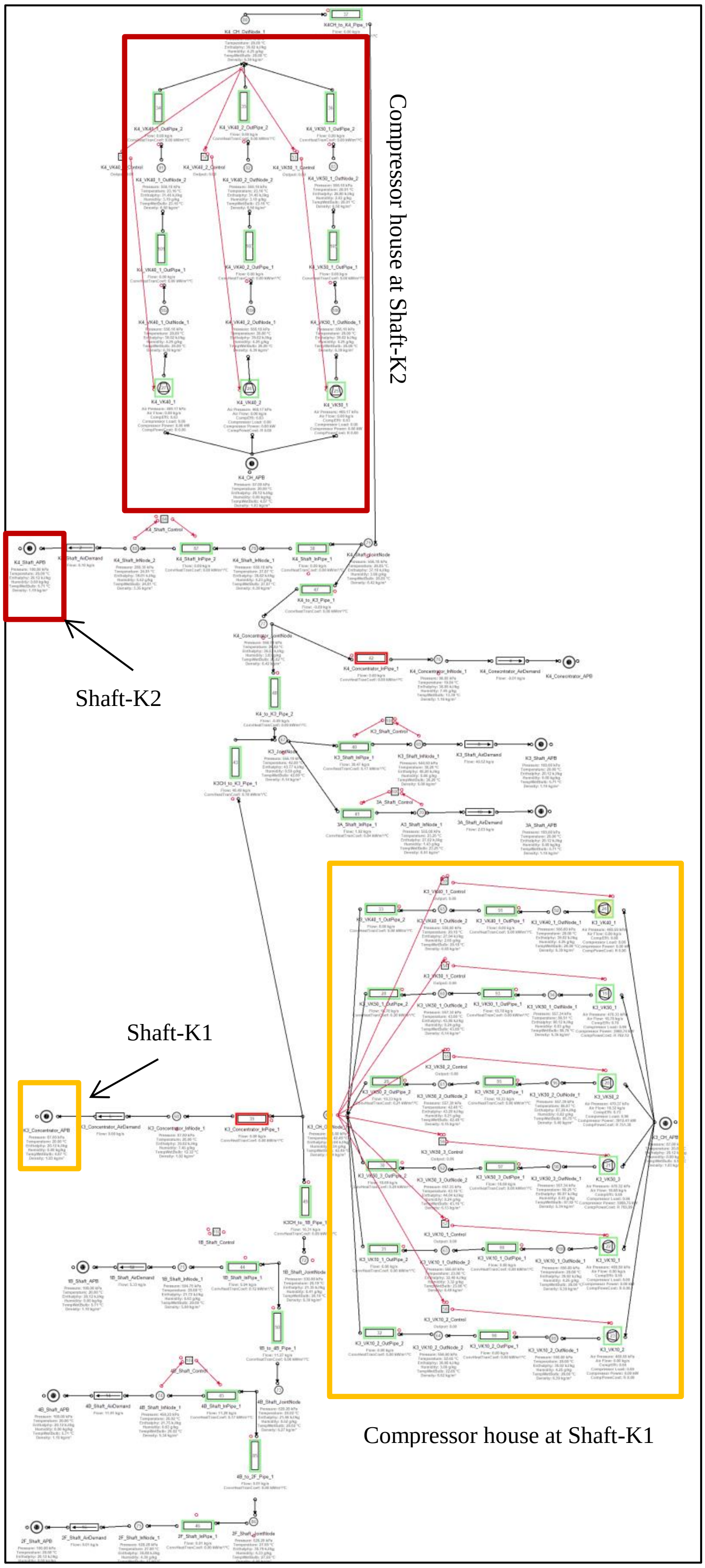


Figure 89: Simulation layout of Case study 2

APPENDIX E : CALCULATOR

Table 37: New simplified high-level investigation calculator

INPUT DESCRIPTION	SYMBOL	VALUE		
Average peak drilling shift power consumption	b	467.3		
Average peak blasting shift power consumption	d	326.9		
ERR DESCRIPTION	**ERR/ ERR INCREASE**	**ESTIMATED POWER CONSUMPTION [MW]**	**ESTIMATED SAVING [MW]**	**ACCURACY WITHIN ACTUAL SAVING [%]**
Pre-ERR	30.04%	–	–	–
Regression model ERR	45.7%	253.6	73.3	109%
Benchmark minimum ERR increase	36%	298.9	28.0	42%
Benchmark average ERR increase	47%	247.5	79.4	118%
Benchmark maximum ERR increase	62%	177.4	149.5	222%