A target-based performance tracker for mine energy monitoring

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Electrical and Electronic Engineering* at the North West University

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Graduation: June 2021

Student number: 33482470

Abstract

Title:	A target-based performance tracker for mine energy monitoring
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Degree:	MEng in Electrical and Electronic Engineering
Keywords:	Energy management, energy efficiency, information system, benchmarking, optimisation

Software systems play a major role in the day-to-day operation of deep-level mines. These systems range from quantifying production and energy use to monitoring seismic activity. As deep-level mines expand to reach more minerals, the software systems become more difficult to maintain, as they need to be scaled up. One aspect which needs constant monitoring through the software systems is the mine energy usage, which affects a significant portion of the mine's profitability. With the constant increase of electricity tariffs, energy-wastage events should be minimised as far as possible to ensure profitability in implemented projects.

Presently, deep-level mines in South Africa primarily make use of a supervisory control and data acquisition (SCADA) to monitor the mining systems. The advantage of a SCADA is its real-time capabilities, which enable constant monitoring of underground processes. This method, however, has two limitations which will be discussed further in this study, namely a lack of a baseline or reference point and a lack of an optimised interface. Due to these limitations, energy-wastage events go unnoticed. Additional methods also discussed in this study to monitor the energy usage include reporting and monthly budgets; however, they carry limitations which make them unable to stop energy wastage as they occur.

In this study, the limitations of the existing energy-monitoring methods are evaluated, and a new monitoring system is proposed. The proposed monitoring system will aim to increase efficiency in implemented projects through mitigating energy-wastage events as they occur. The new method fundamentally focuses on benchmarking the energy use and creates energy usage targets which are project specific. These targets act as a guide which the projects must not deviate from if energy savings in implemented projects are to be maintained. The new targets are implemented in two forms, namely as a new prioritised information system to enhance the SCADA so that monitoring personnel can more easily make informed decisions, and as an SMS (short message service) notification system to track and react to wastage events as they occur.

The proposed monitoring system was implemented on existing projects in a mining group in South Africa, and the case study results show a positive change in addressing unexpected energy-wastage events. It proved to be effective in mitigating energy wastage in a compressed air network integration project to the value of R96 000 through ensuring a compressor is not operated outside of the project scope. This intervention ensured that the project did not deteriorate but maintained savings in a twelve-month period.

In the second case study, the monitoring system mitigated energy wastage in pumping load-shift projects by ensuring pumps were not operated during the more expensive peak hours. In the case study, an annual negative cost impact of R0.2-million is projected to be mitigated using the monitoring system on the specific mining shaft. This value is expected to reach R2-million annually when the monitoring system is implemented on the entire mining group. In the third case study, the monitoring system was successful in mitigating energy wastage in a turbine generator project through ensuring that electricity generation was uninterrupted. Active user engagement was promoted with its optimised visual interface in the fourth case study.

The proposed monitoring system met the objectives of the study and ensured that energy savings were maintained in implemented projects through mitigating wastage.

Acknowledgements

I would like to extend my gratitude to:

- My parents, Rosemary and Absalom Masuku, as well as my brothers and sisters for their continued support and believing in me. Thank you for continuously motivating me to better myself.
- Enermanage (Pty) Ltd and its sister companies for the financial support to complete my study.
- Professor EH Mathews for the unique study opportunity to do my master's at CRCED Pretoria.
- Dr JH Marais and Mr S Taljaard for their academic support and mentorship.
- My colleagues, H Potgieter, J Lodewyk, MC Kendall, and P Hattingh, who assisted greatly in this study.

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Nomenclature

List of abbreviations

DDE	Dynamic Data Exchange
EMS	Energy Management System
ESCo	Energy Service Company
FTP/S	File Transfer Protocol – Secure
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HMI	Human Machine Interface
OPC	Open Platform Communications
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PoD	Point of Delivery
RTU	Remote Terminal Unit
SMS	Short Message Service
SMTP	Simple Mail Transfer Protocol
SQL	Structured Query Language
TCP/IP	Transmission Control Protocol/Internet Protocol
ToU	Time-of-Use
VPN	Virtual Private Network

List of units

kW	Kilowatt	Power
kWh	Kilowatt-hour	Energy
MW	Megawatt	Power
MWh	Megawatt-hour	Energy
R	South African Rand (ZAR)	Currency

Chapter 1

Introduction

1.1 The mining industry in South Africa

1.1.1 Preamble

With the present economic climate of South Africa, mines have become marginally profitable [9]. This is partly due to the rapid increase of electricity tariffs by the nation's electricity supplier, Eskom. Figure 1.1 illustrates the average Eskom tariff increase for the mining industry versus inflation from 2003 to 2019. From the figure, the following can be noted [1], [2]:

- In the period between 2003 until the 2008 electricity crisis, electricity tariffs increased at a steady annual rate of 4.5% and had a total increase of 19.37%. Inflation during the same period had a total increase of 37.46%.
- From the 2008 electricity crisis onwards, electricity tariffs increased at an annual rate of 30% for the first three years; thereafter, they averaged an annual rate of 10% until 2019, with an overall increase of 296% in the period.
- The overall increase of electricity tariffs from 2003 till 2019 was 506%, while inflation only increased by 161%.

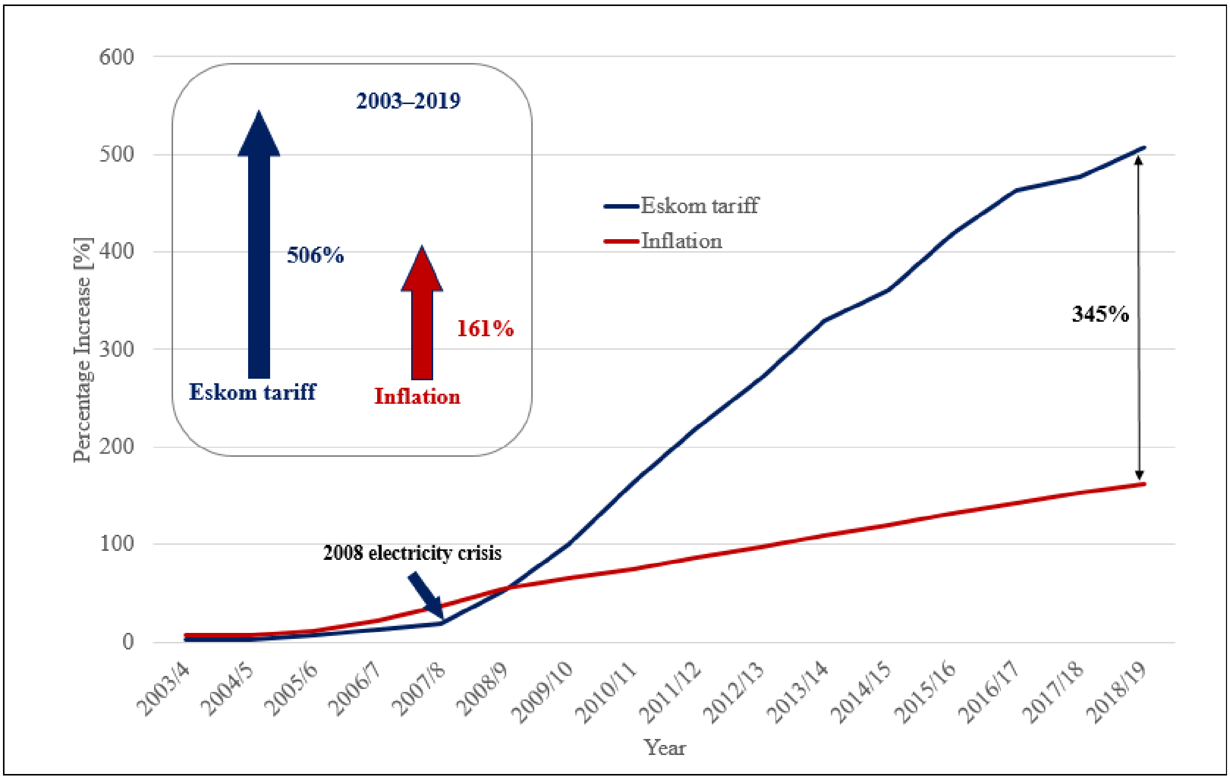

Figure 1.1: Average Eskom tariff increase versus inflation from 2003 to 2019 (adapted from [1], [2])

Based on the approved tariff increases for 2020 and 2021, the total increase in electricity tariffs from 2003 to 2021 will be 520% [10]. This rapid increase in electricity tariffs continues to strain the South African mining industry thus leading it to become more wary of its energy usage.

In 2019, the two largest mining companies in South Africa, Harmony and Sibanye Stillwater, had a combined energy usage of 9 031 000 MWh, which has a cost of approximately R7.5-billion [11], [12]. This poses a threat with regard to profitability as the tariffs continue to increase. Energy awareness and reduction measures now play a major role in maintaining profits [9].

1.1.2 Overview of the major energy users in deep-level mines

In order to save energy[1] in deep-level mines, the mining processes must be identified. A typical breakdown as illustrated on Figure 1.2 is revealed when grouping the major energy users for deep-level mines. As illustrated, the highest energy user is compressed air followed by the mining processes and then pumping [3], [4].

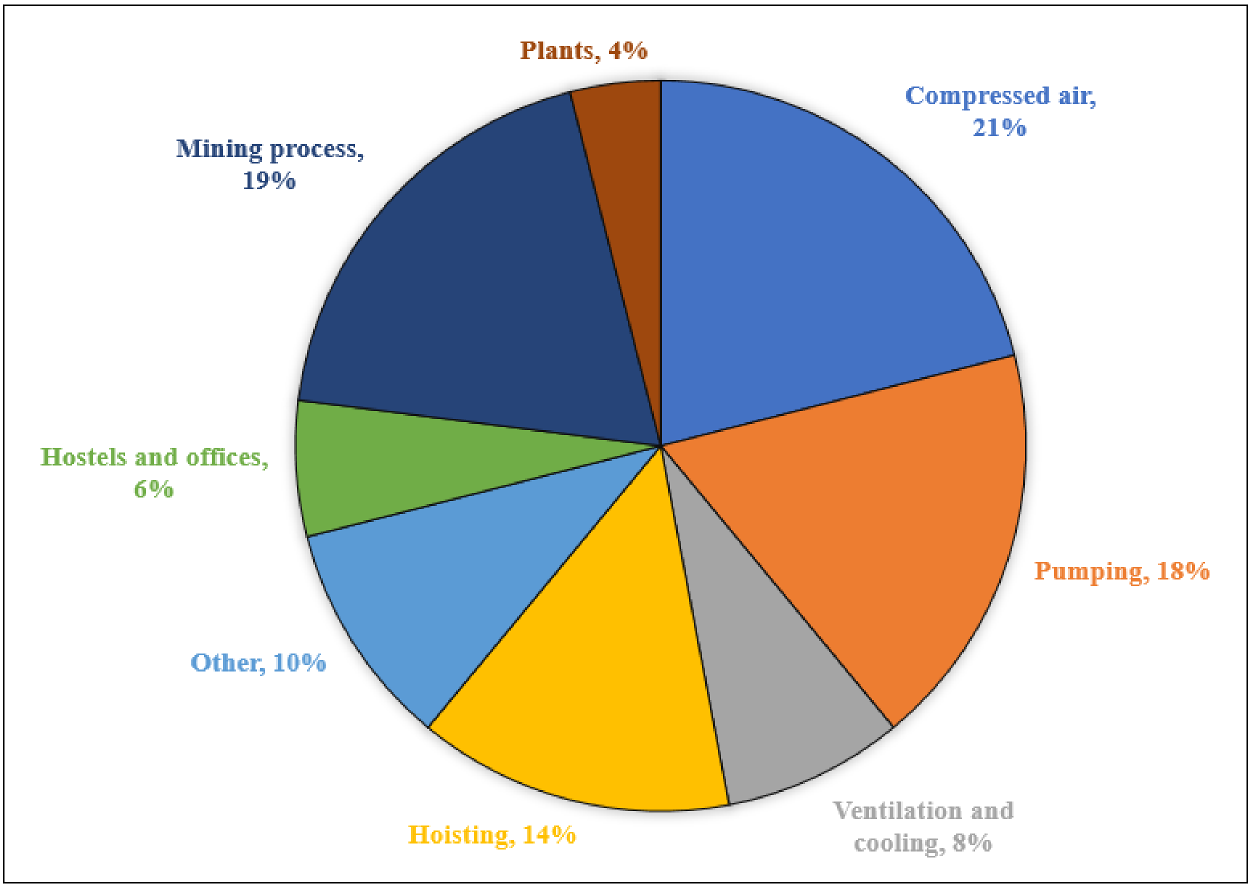

Figure 1.2: Typical deep-level mine system energy consumption (adapted from [3] [4])

[1] In this study, the term "energy" is with respect to electrical energy.

Prior to the implementation of new projects, the high energy users must first be identified. This ensures that a higher priority is set on mining systems which will have the most significant impact in reducing energy usage. A similar approach is used when identifying which implemented projects need maintenance and reviving first. Mining systems such as hoisting are required to operate uninterrupted. This makes it challenging to implement let alone maintain energy saving projects [9], [13].

1.1.3 Existing energy management and cost saving initiatives

After the main mining systems have been identified, the energy saving projects can be implemented. The types of energy saving projects implemented in gold mining systems as illustrated on Figure 1.2 are the following [4], [9]:[2]

- Underground audits (leak fixing and maintenance)
- Demand-side management (DSM)

Underground audits (leak fixing and maintenance)

Due to the vast nature of mine system networks such as compressed air and water reticulation (pumping), leaks are inevitable. The most common areas where these leaks occur are the column flanges where the pipe sections are joined. For compressed air networks, the presence of leaks decreases the network pressure and forces compressors to operate at increased loads, leading to an increase in energy usage. For water reticulation networks, leaks increase the quantity of water which has to be pumped out to surface, leading to an increase in energy usage [4], [14].

When instrumentation is not installed on the decline tunnels[3] that measure flow usage for either compressed air or water, a manual data audit is required. This audit obtains data that will be used to implement corrective measures [15]. These corrective measures involve repairing the leaks which will lead in turn to improved efficiency [4], [14].

When the initial leak fixing audit is completed, general efficiency improvement of the mine can be performed. This involves using the data obtained to perform benchmarking to identify which areas are being oversupplied [15]. Reducing this oversupply will reduce the load on machinery and in turn lead to increased energy saving. An additional advantage of the audits is the identification of dangerous operating conditions mainly due to excessive heat and insufficient air. This ensures regulatory compliance which mines are ordered by law to follow [16].

[2] Underground audits are split from DSM techniques to separate common methods with broader ones.
[3] Decline tunnel: This is a tunnel driven between the base and the surface of a mine to facilitate transportation of equipment and vehicles in and out. Source: https://ohiovalleymining.com/.

Demand-side management: Time-of-use improvement

Most mining companies in South Africa are billed based on Eskom's Megaflex tariff structure. This entails that the electricity tariffs vary depending on the time of day (or "time-of-use"). This tariff structure makes use of three time frames, namely "standard", "peak", and "off-peak". Tables 1.1 and 1.2 indicate the specific time frames for the time-of-use (ToU) tariff structure, depending on the season [1], [17].[4]

The high-demand season is the Southern Hemisphere winter months of June, July, and August, and the rest of the months fall under the low-demand season. As shown on Tables 1.1 and 1.2, the tariff costs drastically increase, depending on the season. For the low-demand season, the transition from the off-peak tariff to the peak tariff increases by 101%, and for the high-demand season, this increase is 409%. These increments are in the order of millions of Rands due to the high energy usage in South African mines [11], [12].

Table 1.1: Eskom tariff table (low-demand season)

	Weekday	**Saturday**	**Sunday**	**Cost**
Standard	06:00–22:00 (unless peak)	07:00–12:00 18:00–20:00	None	94.2 c/kWh
Peak	07:00–10:00 18:00–20:00	None	None	130.48 c/kWh
Off-Peak	22:00–06:00	20:00–07:00 12:00–18:00	All day	64.89 c/kWh

Table 1.2: Eskom tariff table (high-demand season)

	Weekday	**Saturday**	**Sunday**	**Cost**
Standard	06:00–22:00 (unless peak)	07:00–12:00 18:00–20:00	None	122.19 c/kWh
Peak	06:00–09:00 17:00–19:00	None	None	371.07 c/kWh
Off-Peak	22:00–06:00	20:00–07:00 12:00–18:00	All day	72.77 c/kWh

In order to benefit from this tariff structure, load shifting is performed. This involves moving the process' energy consumption outside of the more expensive peak periods. This not only has financial benefits but also helps reduce the load and demand on the national electricity distribution grid [18], [19].

[4] Tariff used: 2019-2020 Eskom Megaflex cost ≤300 km ≥500 V <66 kV + admin

Figure 1.3 illustrates a typical load shift profile of a water reticulation system. As illustrated, the dotted load curve is lower than the solid load curve during the peak periods (highlighted in red) and is higher in the off-peak and standard periods. This shows how the load has been shifted from the times with higher tariffs to the times with lower tariffs.

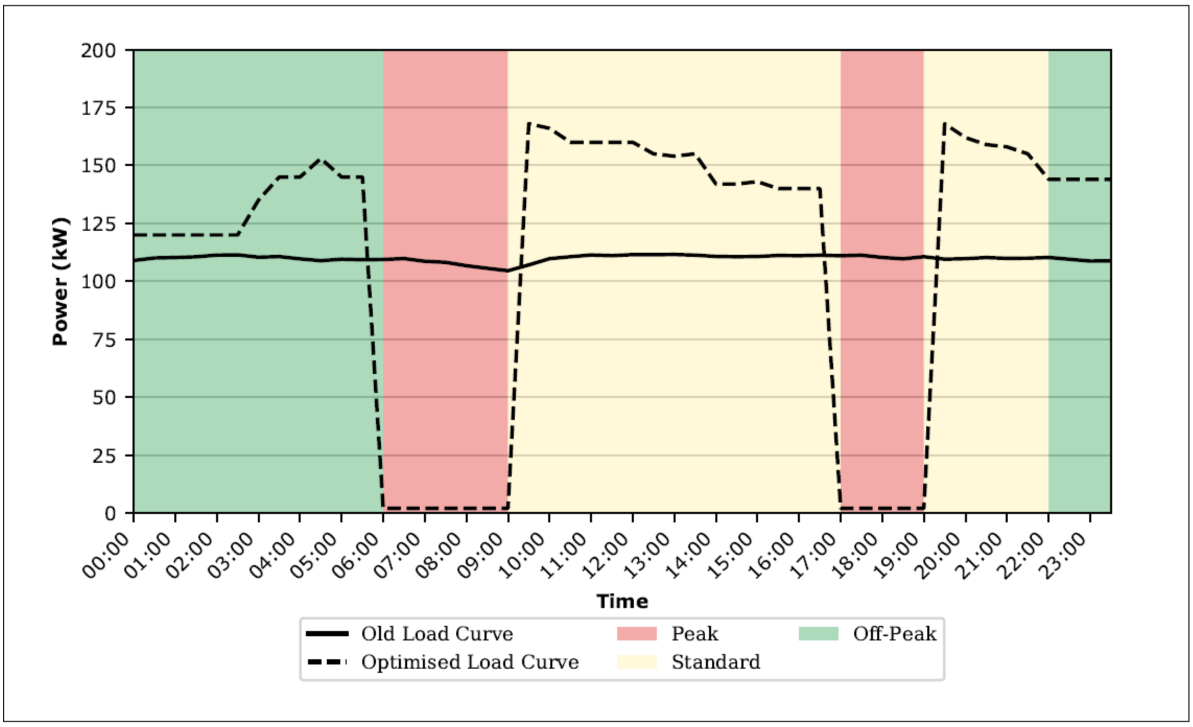

Figure 1.3: Load shift power profile

Water reticulation systems are good candidates for load shifting, as they make use of storage dams as buffers to manage the water. Pumping is maximised during standard and off-peak times in order to reduce the storage dam levels in preparation for the peak period. Because the storage dams are at their minimum, water can still flow during the more expensive time periods without the need to pump it out [20].

The daily energy cost can be calculated using the tariff values on Table 1.2. The total energy used in both load curves is 2 600 kWh; however, performing a load shift reduces the total energy cost by 40%, from R4 300 to R2 600. Load shifting is worthwhile considering its cost saving possibilities, especially during the high-demand season.

Demand-side management: Peak clipping

Peak clipping, otherwise known as load reduction, focuses on reducing the power consumption during Eskom's peak demand periods (refer to Table 1.1 and 1.2). The implementation of peak clipping initiatives has a positive impact on reducing the system's total electrical energy consumption [9].

Figure 1.4 illustrates a power profile where a peak clipping initiative was implemented. As illustrated, the dotted and solid load curves are the same throughout the day, but during the evening peak period (highlighted in red between 17:00 and 19:00), they deviate. The dotted load curve is lower than the solid load curve, indicating that the load was reduced just for that period.

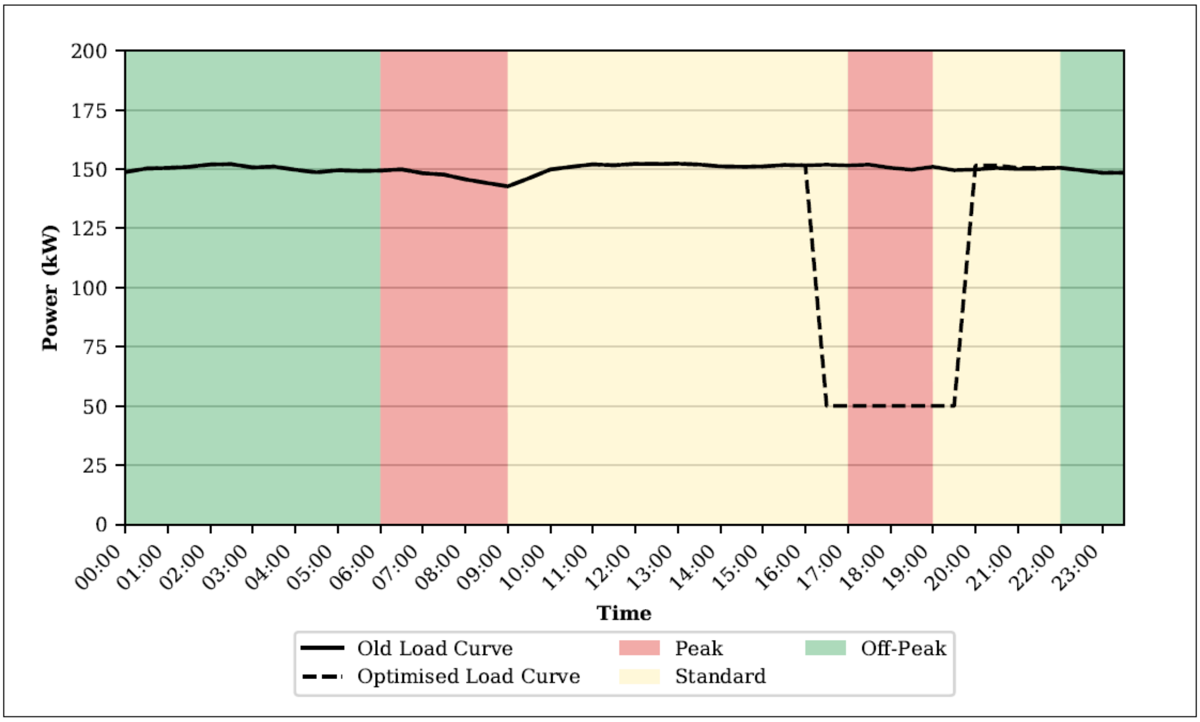

Figure 1.4: Peak clipped power profile

Peak clipping initiatives not only save energy but also assist with lowering the demand required for the national grid. Peak clipping initiatives are often implemented on ventilation, compressed air, and refrigeration systems [9].

Demand-side management: Dynamic control of pneumatic equipment

In deep-level mines, underground mining pressure requirements change according to a daily schedule. The pneumatic equipment for pumping and compressed air operated during different periods of the day uses different pressures [21].

Considering a compressed air network, it is crucial that the compressors supply enough air to match the dynamic requirements. This will ensure that the pneumatic equipment operates optimally and that production levels are met. This is done by calculating the pressure set points of the compressors by considering the consumers' requirements, pressure drops, auto compression, and flow loss. The calculation results are then used to determine when the compressors should be stopped or started [14], [21].

Optimising the control will help reduce cases where oversupply occurs. Reducing oversupply gives rise to opportunities where machinery can be completely stopped. This has two benefits, namely energy saving and a reduction in maintenance costs [14], [21], [22].

1.1.4 Sustainability of implemented projects

The performance of implemented DSM projects can be expected to decrease over time. This decrease in performance is attributed to various reasons, the most common being production constraints, improper maintenance, and negligence [5], [23]. Examples of each are listed below:

- **Production constraints:** An increase in production targets results in an increase in the use of machinery. This often leads to the reversal of implemented projects, as they are percieved to hinder the production output.
- **Improper maintenance:** Conducting maintenance on machinery too late or replacing machine parts with the wrong specifications negatively affects the project performance.
- **Negligence:** Control room operators often override or do not follow the prescribed schedules. This negatively affects the project performance.

Figure 1.5 illustrates the historical performance of a load shifting project implemented on cement mill production plants. The first three months were the performance assessment[5] period which the project performed well above the target of 2.55 MW. In the following months, there was a gradual decrease in performance leading to the project performing 76% below the target in Month 24.

[5] Performance assessment: Period which the project is evaluated to prove its feasibility.

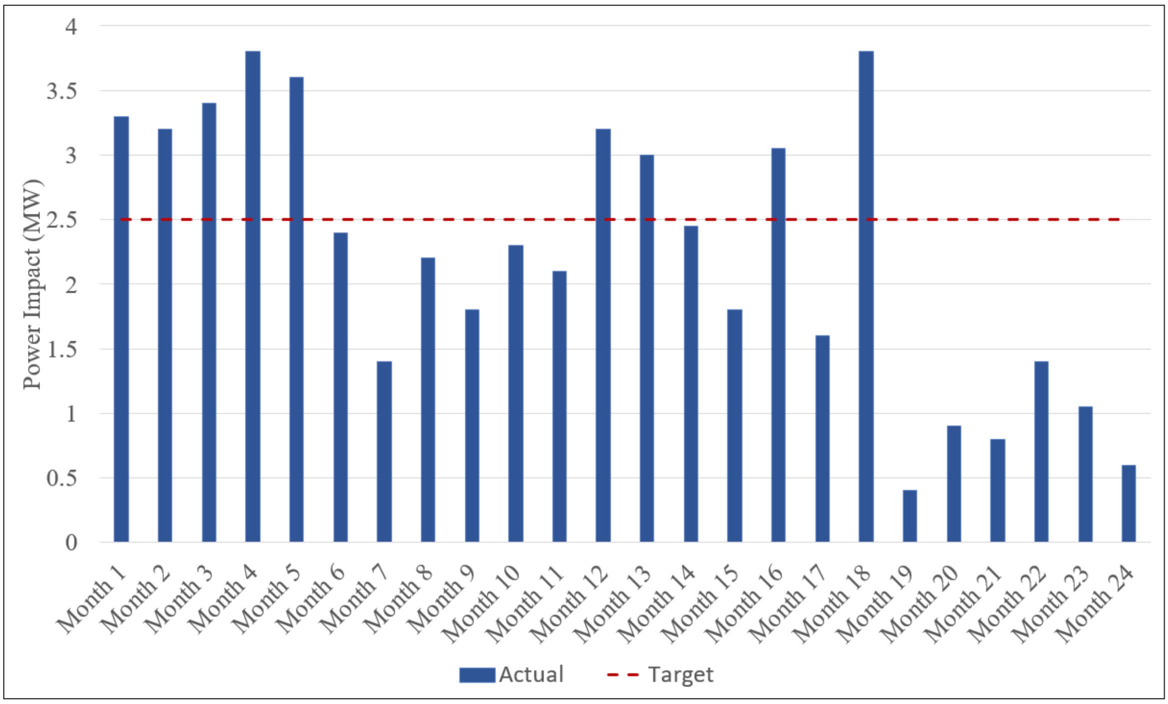

Figure 1.5: Gradual decrease of performance in a load shifting project [5]

Figure 1.6 illustrates the deterioration experienced on a project implemented on a refrigeration system of a typical gold mine. The project over-performed in the first three months of the performance assessment; however, on Month 4, the performance drastically decreased and was below the target of 2.8 MW by 57%. The project continued to under-perform, and overall performance gradually decreased throughout the months. On Month 24, the impact was only 1.2 MW.

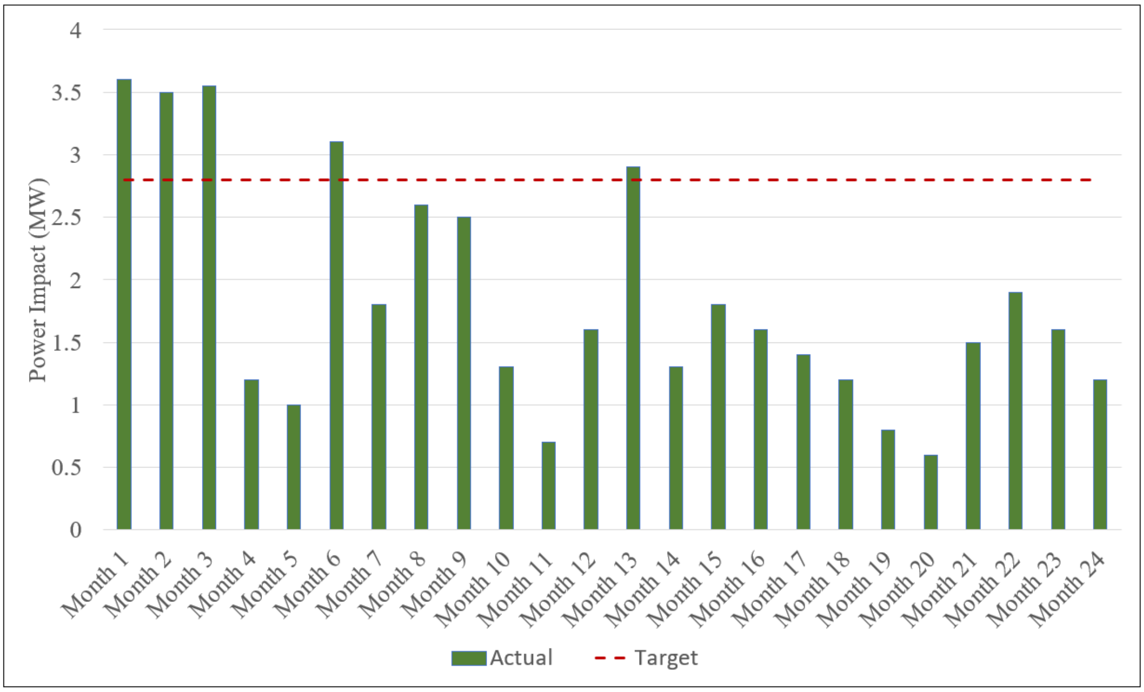

Figure 1.6: Gradual decrease of performance in a refrigeration project [6]

As illustrated in Figures 1.5 and 1.6, project performance gradually decreases over time due to three main reasons previously mentioned: production constraints, negligence, and improper maintenance. The maintenance of existing projects is needed to guarantee profits with the rapid increase of electricity tariffs and the almost inevitable deterioration [5], [6].

1.1.5 Present status of the South African mining industry

Presently in South Africa, the electricity provider, Eskom, has increased tariffs to levels much higher than the inflation rates as illustrated on Figure 1.1. Owing to this increase, energy saving measures have switched from being an optional cost reduction to a necessity. The implementation of these projects alone does not, however, guarantee energy savings, as projects begin to deteriorate in the first three months as shown in Section 1.1.4. The maintenance and monitoring of implemented project savings is crucial to ensure that their performance does not deteriorate. Section 1.2 focuses on the strategies used to monitor as well as maintain the energy savings of the projects.

1.2 Literature review

This section highlights different techniques used in literature to monitor and benchmark mine energy usage and project performance. These techniques are particularly applied to deep-level gold and platinum mines.

1.2.1 Energy monitoring solutions for deep-level mines

As mentioned in Section 1.1.5, South Africa's mining industry needs to prioritise energy saving project maintenance. Process and financial monitoring are conducted on the mining systems in order to keep track of the ongoing processes. In the South African mine context, the main techniques which are presently being used to monitor the energy saving initiatives are listed below [9], [24], [25], [26]:

- Reporting (energy and financial)
- Supervisory Control and Data Acquisition (SCADA)
- Billing (electricity)
- Information systems

Notification systems in the form of electronic mail (Email) and SMS have been introduced into the mining industry. Mouton *et al.* [27] investigated using the Global System for Mobile Communications (GSM) cellular networks to communicate with the motor protection relays and to effectively control electric motors. This was later adapted into the mining industry by Du Plessis [28] who used SMS notifications to report on diagnostics for Energy Management System (EMS) applications on remote sites. Although these notifications were not directly linked to reporting energy usage, it is worth mentioning their versatility to be used in energy monitoring.

Reporting (energy and financial)

Energy reporting is the verification, monitoring, and analysis of the use of energy. It involves "closing the loop" by compiling information gathered from monitoring processes in a form that will enable an ongoing control of energy use, verification of acquired savings, and the achievement of set targets [29], [30]. This method is the most widely used in terms of its versatility across all different factions within the mines' hierarchical structure [24]. It can range from high-level reporting, which includes the total energy usage of the mine as well as the total cost combined into only a few values for the stakeholders, to its low-level form, which includes the different mining systems per shaft for a more in-depth analysis of the processes [24].

The key to accurate reporting is firstly identifying the purpose of the report and its target audience. Using the typical mine organisational structure from shaft engineer to the CEO, a report with the desired purpose can be generated. A shaft engineer would desire a report which focuses on the main mining systems within the shaft itself, and the pumping technician would desire a report with only one of the systems, such as pumping. The report which will go to the CEO will only contain profit or loss of all the mining operations [24].

A major obstacle of this technique in terms of monitoring project performance is finding the suitable frequency of the report generation. If the reports are sent hourly or daily, they soon become overwhelming. This will make it difficult for the recipient to read the contents and act accordingly. If the reports are generated within a wider time frame, such as monthly, there is a higher chance of them being treated as high priority; however, owing to the wider time frame, most operational inefficiencies go unnoticed and thus cannot be stopped in time.

SCADA

This is a control system architecture which consists of computers linked to peripheral devices, Programmable Logic Controllers (PLCs) and Proportional Integral Derivatives (PIDs), to interface with the machinery on deep-level mines. SCADA is able to perform real-time operations to the devices as well as display their current operation state by using communication protocols such as Open Platform Communications (OPC), Dynamic Data Exchange (DDE), and Network DDE. The most widely used SCADA communication protocol is the OPC protocol. This is the industry standard, and the specifications are defined by the OPC Foundation [31]. Hardware communication protocols used by PLCs are translated into the desired software protocol used by the SCADA [7], [32], [31].

Figure 1.7 illustrates the typical SCADA system architecture with the following description [7]:

- **Field Level:** This is the lowest level which contains the sensors and signal transmitters.
- **Direct Control:** Contains the micro controllers which are programmed to control the machinery.
- **Communication:** This is the system which allows communication between the remote devices and user workstations.
- **Workstations:** Used for the human interface with the microcontrollers, often referred to as the Human Machine Interface (HMI), it contains the screens and graphics used by operators to trigger manual operations.

– **Configuration:** This contains the data server computers responsible for maintaining the configuration software for the SCADA.

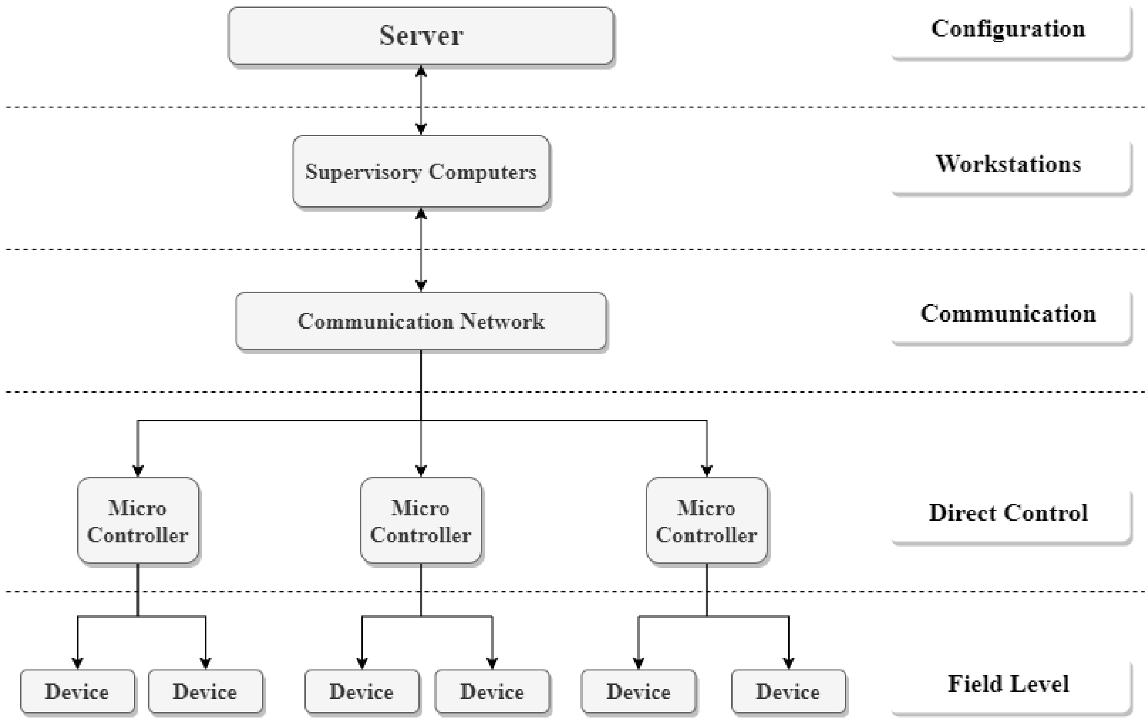

Figure 1.7: Typical SCADA System Architecture (adapted from [7])

Control room operators are then able to make supervisory decisions using the HMI to adjust or override normal Remote Terminal Unit (RTU) controls using the compiled data [7], [33]. The data can also be stored in a data historian to allow trending and other post-analytical auditing [34].

The limitation with using the SCADA for energy monitoring is that the visual interfaces used in the operator workstations of Figure 1.7 are not always fully optimised in terms of overcoming cognitive overload [35]. As more data is needed from the underground processes as the mine expands, the Graphical User Interface (GUI) will often become congested as illustrated on Figure 1.8. This overwhelms the operators and monitoring personnel, as they must monitor normal operation as well as energy saving initiatives. The illustration on Figure 1.8 only depicts one portion of the overall system; a typical SCADA system will contain multiple screens with multiple mining systems, such as compressed air and refrigeration [36], [37].

This causes cognitive overload, as there is too much information on the screen and decisions tend to be ill-advised [38], [39]. In addition to the congestion, the SCADA normally does not have advanced analytical tools. This poses a challenge for control operators and monitoring personnel to gauge the impact of their actions [36], [37].

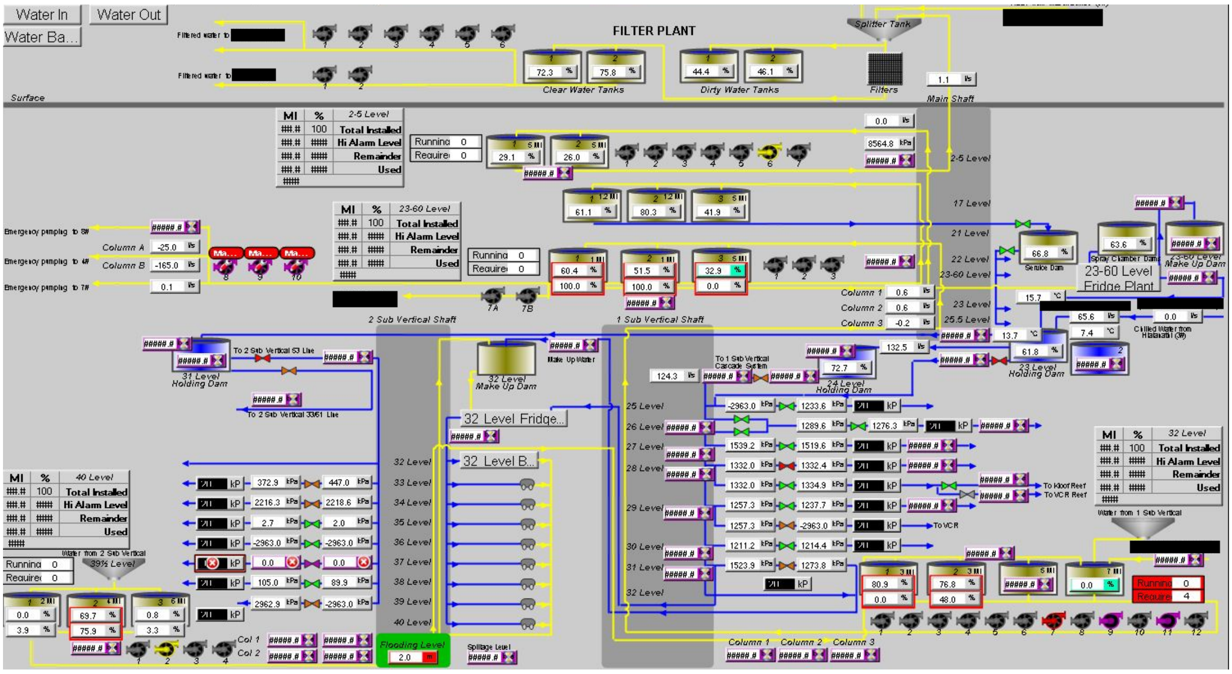

Figure 1.8: SCADA water reticulation system snippet

Billing (electricity)

Energy meters are installed on the mining shafts by the electricity supplier (Eskom) to track the energy usage. The mine installs their own energy meters at similar locations for verification. The energy budget is estimated monthly using the data from the mine's energy meters. The daily budget is then calculated as the fraction of the monthly budget during a specific billing period. On a monthly basis, the mine is invoiced for the usage. This method is used for energy monitoring and management through comparing the invoiced bill to the monthly estimated budgets and noting the differences [40].

The limitation with this method is that it is only executed once a month; therefore, energy-wastage events cannot be tracked as they occur. As a budgeting tool, it is very efficient; however, it falls short as an energy monitoring tool because wastage events are only identified long after they have occurred.

Information systems

These systems primarily operate with historical data to provide analytical solutions for monitoring the energy usage. They range from web-based applications to additional extensions on the SCADA itself. The users of these systems are mostly the management personnel in the mines' organisational structure because these information systems do not only provide raw usage values, but also give detailed information which includes the forecasting of project performance [24], [41].

Information systems allow for more unique analysis by incorporating benchmarking and performance tracking to the general usage statistics. This helps with more structured monitoring because it eliminates the need for displaying too much information, such as in the case with reporting and the SCADA.

Information systems, however, also face the same visual flaws as the SCADA when they are not designed well. Congestion on the screens will lead to ill-advised decision-making caused by cognitive overload [39].

Mobile notifications

Notifications on mobile devices are convenient in that they are accessible at any time, much like a physical presence [42]. This need for a physical presence is a solution to curb the energy-wastage events which often occur when the mining systems are not being actively monitored.

Studies [43], [44], and [27] showed that cellular networks can be incorporated directly into industrial equipment. Van Jaarsveld [43] monitored the condition of mining equipment, and this gives scope to use these same networks to provide constant energy management and monitoring. Yumang *et al.* [44] used SMS notifications as an emergency to alert a community to potential flooding.

Much like the SCADA and reporting, however, these systems can overload the recipients. Studies [45] and [46] investigated the importance of relaying the message in order to promote user adoption and engagement. This involved finding the right frequency as well as the content displayed in order to prompt the user without overwhelming them. Avoiding overwhelming the user in notification systems is important because it guarantees that the recipient will act promptly and not perceive the message as insignificant [45], [46].

1.2.2 Performance tracking and benchmarking energy usage

For a project to succeed, its performance is continuously monitored, and analytical tools are used to gauge the progress. In the mining industry, statistical models are used to track performance in the form of baselines and targets [8]. The following sections give more detail on the types of statistical models used to benchmark energy usage.

Baseline model development

According to ISO 50001 [47], the most important step in energy planning is establishing an energy baseline. Energy baselines are important because they provide a quantitative comparison for the energy performance [48], [49]. Energy baselines are determined from a position of knowledge through analysing historical performance data. The data used for the energy baselines should incorporate a substantial period of time so as to include all possible variations of the energy drivers [50].

When creating the baseline, the following should be correctly identified [50]:

1. The reference period selected from the most suitable time period (group of data).
2. The energy drivers influencing the overall energy behaviour of the system being analysed.

When selecting the most suitable time period for analysis, Benedetti *et al.* [50] identifies three common methods:

1. Considering the most recent available set of data. This ensures that the baseline creation does not include previous structural, technical, or technological configurations of the analysed item.
2. Considering the best energy performance from the data set. This choice poses a challenge in terms achieving the energy objectives and targets; therefore, it must only be considered when the focus is continuous improvement.
3. Considering the most constant and stable energy behaviour from the data set. This choice gives the highest probability of the performance being the same in the future. It is normally selected when the previous two methods are not applicable.

Figure 1.9 illustrates a typical electricity reticulation level of detail. Level 0 is the Point of Delivery (PoD) level which contains the energy meters used by the electricity supplier. Level 1 contains the grouped systems' energy meter panels, and Level 2 contains the energy meters on the actual machinery. When more than one level of detail is considered for the creation of the baselines, it is possible to create them through either a bottom-up or top-down approach [50], [51].

The top-down approach first involves defining high-level energy baselines and then obtaining one of the baselines of the following levels as the difference between the higher-level baseline and the baselines of its same level. Using Figure 1.9, this entails obtaining the Level 0 baselines and then working down. It is normally adopted when the energy cost is used as the foundation of the baseline creation [50], [51].

The bottom-up approach is the reverse, defining low-level energy baselines first and then obtaining the higher-level baseline as the sum of the lower-level baselines. Using Figure 1.9, this entails obtaining the Level 2 baselines and then working up. This procedure is normally adopted when the energy consumption is the foundation of the baseline creation.

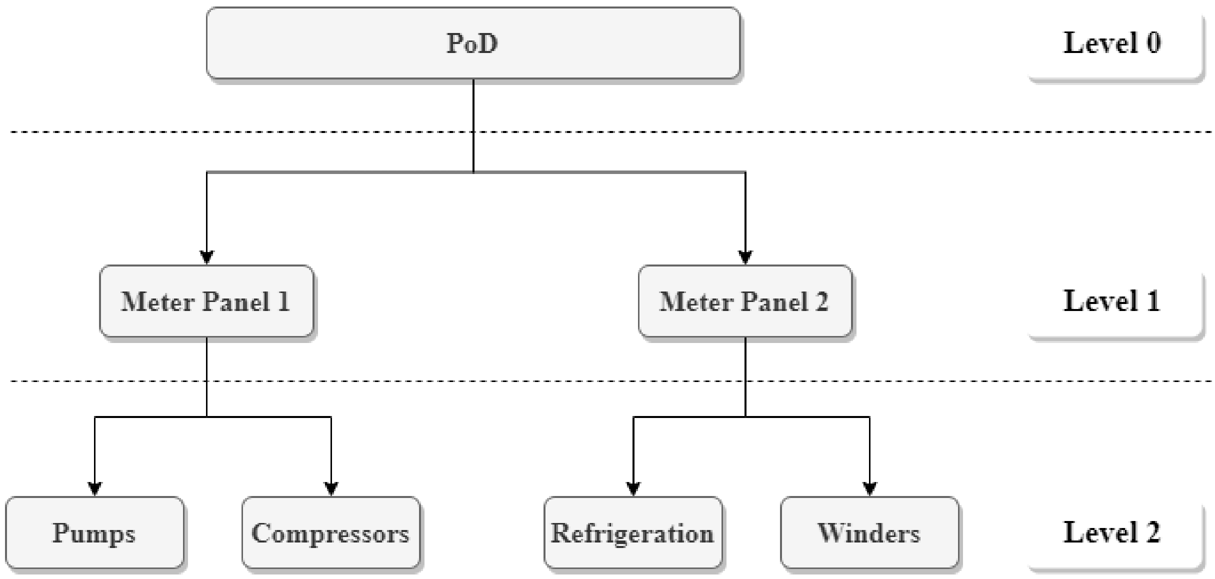

Figure 1.9: Typical levels of detail (for illustrative purposes only)

Using either the bottom-up or top-down approaches introduces a margin of error in estimating the energy baselines; however, the possibility of having ill-matched baselines at different levels is removed [50], [51], [52].

Target model development

Targets are a measure of what needs to be achieved. All targets have two measuring metrics, namely [29]:

- The measure of the level which can be reduced, and
- the time it will take to reduce the measure.

Since the baselines are normally chosen from a period where the energy saving projects were not implemented, targets then become the metric which quantify the potential additional energy savings over and above the baseline savings. To set up the desired targets or objectives, the original baseline, which has already been established, is used as the starting point. When using the top-down baseline approach, the desired overall energy cost saving is established. This cost is divided down the individual systems to establish a potential additional saving [50], [51], [53], [54].

When using the bottom-up baseline approach, the individual systems are each allocated energy consumption limits [50], [51]. When setting the targets, it is important to consider the feasibility of achieving the desired performance specified by the energy analysis [29].

The constant baseline model

The constant baseline model is used to represent systems with steady operational characteristics. To develop the constant baseline model, the average profile is calculated for each operational model included in the data group. The calculated profiles are never adjusted to factor in system changes [8], [55].

The constant baseline model is summarised by the following equation:

$$BM_C = EU_{BP} \tag{1.1}$$

Where:

BM_C = baseline model: constant
EU_{BP} = the energy usage during baseline period

Figure 1.10 illustrates three profiles representing different operational modes. These operational modes are calculated by averaging the data group according to the required mode such as "Saturdays" or "Sundays". For example, the "Sunday" profile will contain averaged data in a specific period for Sundays only.

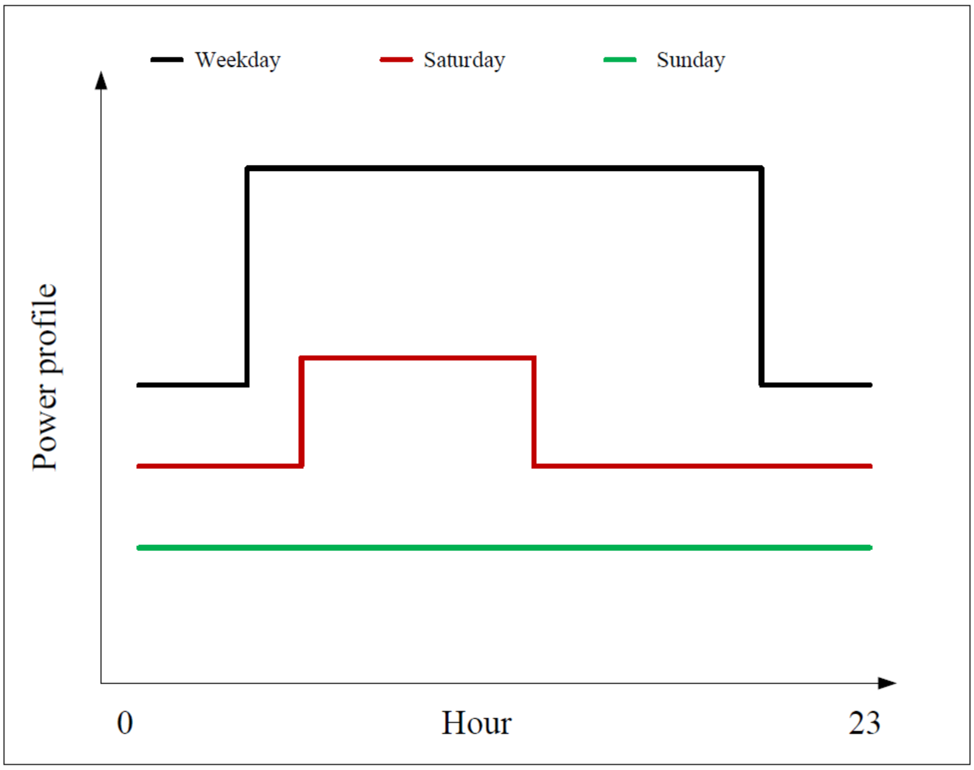

Figure 1.10: Constant baseline model – Average profiles (adapted from [8])

The energy-neutral baseline model

The energy-neutral baseline model is developed similarly to the constant baseline model; however, it differs slightly in that it uses energy usage as a reference for adjusting the model. The profile shape remains unchanged, but the amplitude is adjusted to depict a particular scenario for the system operation [8], [55].

The energy-neutral baseline model is summarised by the following equation:

$$BM_{EN} = EU_{BP} \cdot (\frac{RE_{BP}}{RE_{AP}}) \tag{1.2}$$

Where:

BM_{EN} = baseline model: energy-neutral
EU_{BP} = the energy usage during baseline period
RE_{AP} = the reference energy for assessment period
RE_{BP} = the reference energy for baseline period

Figure 1.11 illustrates the basic concept of the energy-neutral baseline model. It is summarised by the following steps:

- **Step 1:** Select a reference point. This is a specific time period for calculation.
- **Step 2:** Calculate the reference point energy consumption. This is done for the assessed profile (B) and the baseline (A).
- **Step 3:** Calculate the scaling ratio. This is (B) divided by (A).
- **Step 4:** Adjust the baseline profile, depending on the scaling ratio. This can either be up or down.

The resulting adjusted profile has the same reference energy as the assessed profile.

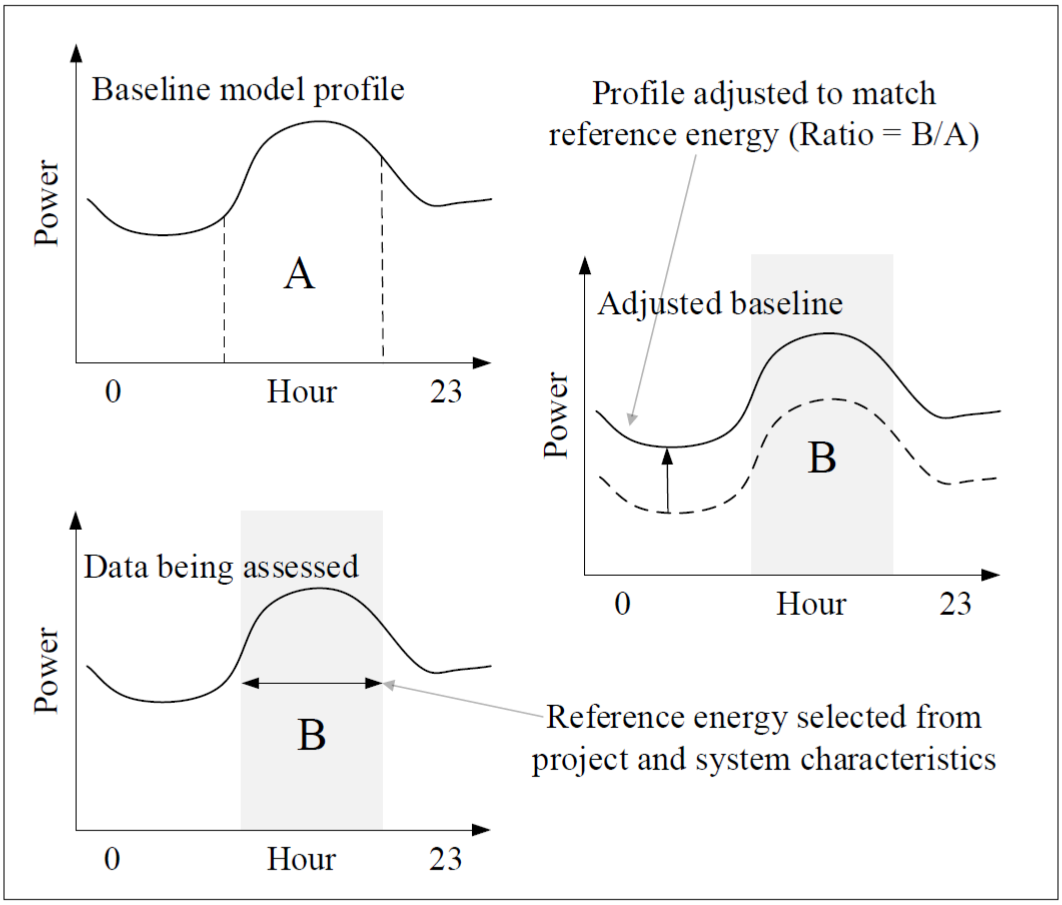

Figure 1.11: Energy-neutral baseline model (adapted from [8])

The regression baseline model

By definition, a regression model aims to describe the relationship between a dependent variable and one or more independent variables. Much like the energy-neutral baseline model, the regression baseline model also uses a scaling factor to adjust the amplitude; it links changes in system variables to changes in system power consumption [8], [55].

Figure 1.12 illustrates how independent variables are matched to a dependent variable such as system power consumption. Illustrated on Figure 1.12 is a system baseline data set which is used to obtain a relationship between ambient temperature and cooling power. Ambient temperature is an excellent example of an independent variable because it affects the cooling power consumption but not the reverse [8].

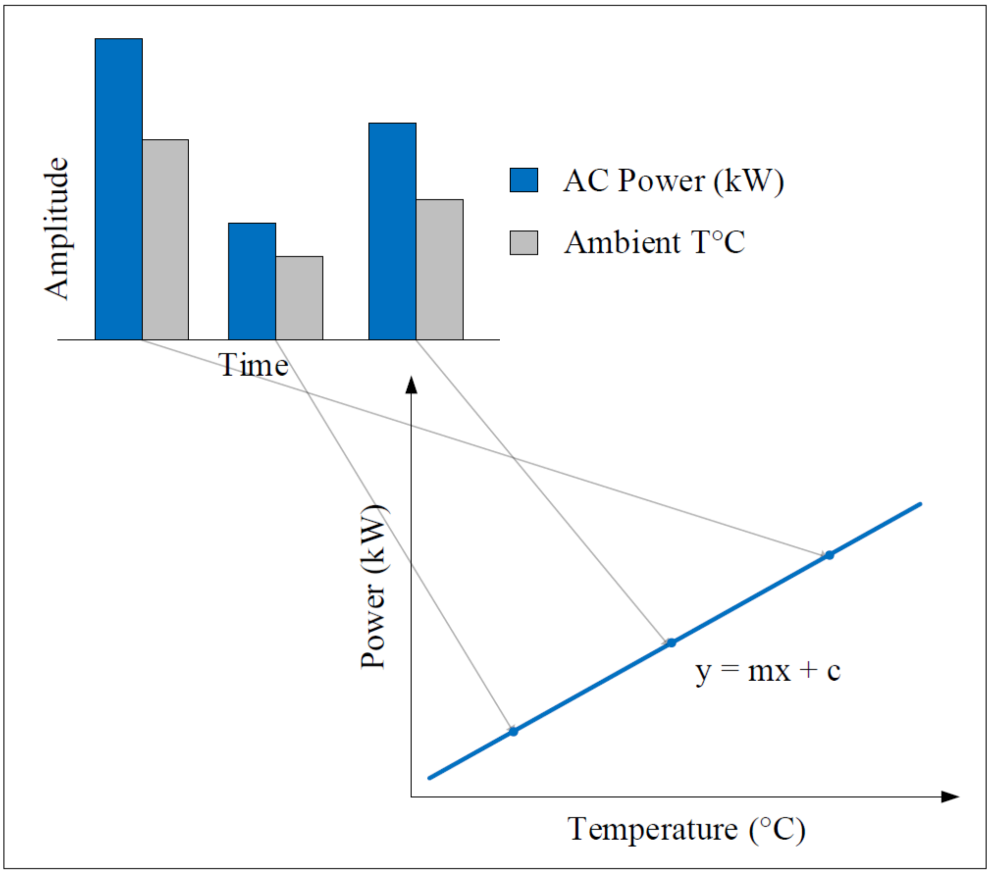

Figure 1.12: Regression baseline model (adapted from [8])

This model is linear and can, therefore, be represented by Equation 1.3:

$$y = mx + c \tag{1.3}$$

Where:

y = the coordinate of the vertical axis
m = the gradient of the line
x = the coordinate of the horizontal axis
c = the intercept with the vertical axis (y)

The error $E(m,c)$ is derived using the variables m and c from Equation 1.3 and is shown on Equation 1.4.

$$E(m,c) = \sum_{k=1}^{n} [y_k - (mx_k + c)]^2 \tag{1.4}$$

Where:

n = the total number of data points
k = the k^{th} data point

The objective is to minimise the error with respect to parameters m and c. The minimum error will exist when the first derivative of the parameters m and c is zero [55].

Impact of baselines and targets on projects

Figure 1.13 illustrates two power profiles denoting the actual usage against the baseline usage. To calculate the performance, the actual profile is compared to the baseline profile. For energy saving projects, if the actual profile is under the baseline profile, the better the project is performing [56].

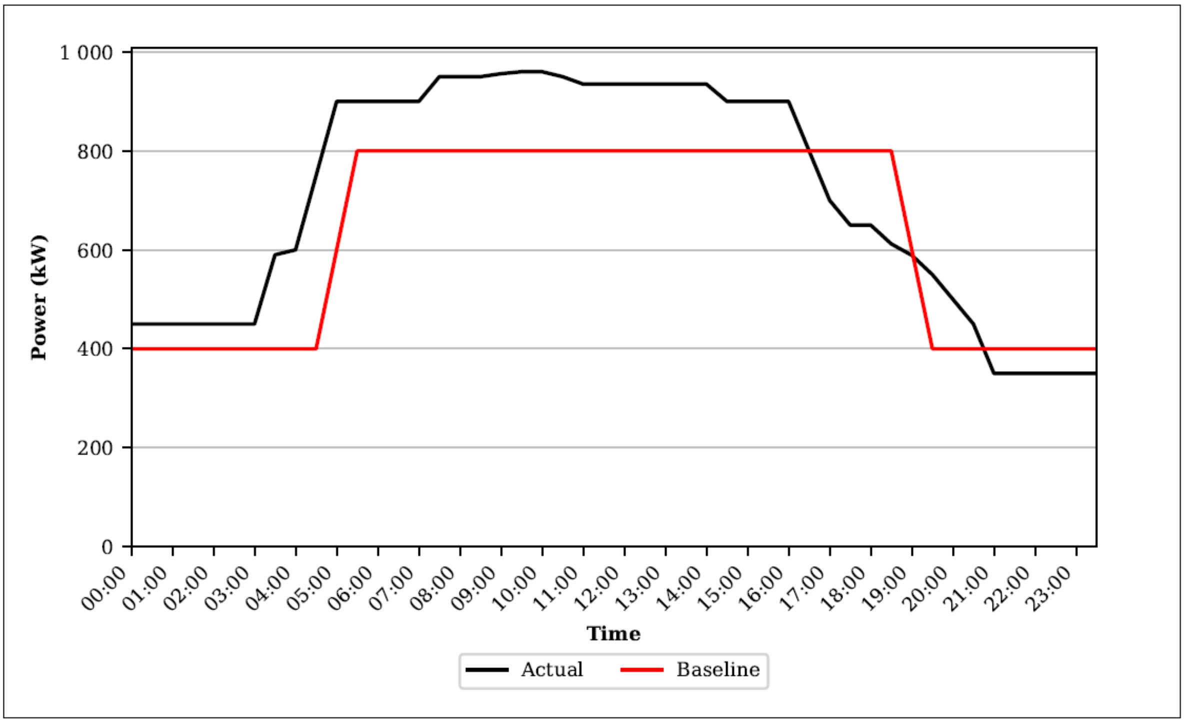

Figure 1.13: Baseline profile versus actual usage

This performance can be measured as an energy cost saving as shown on Equation 1.5. This is standardised by the ISO 50001 and the International Performance Measurement and Verification Protocol [56], [57].

$$ES = EU_{BP} - EU_{RP} \tag{1.5}$$

Where:

ES = energy saving
EU_{BP} = the energy usage during the baseline period
EU_{RP} = the energy usage during the reporting period

Figure 1.14 illustrates a target profile against the actual usage and baseline. The difference between the target and baseline is that the target aims to quantify the effect of pushing the implemented project's performance to realise additional savings. This sets a required limit for the energy usage in order to maximise the potential additional energy savings.

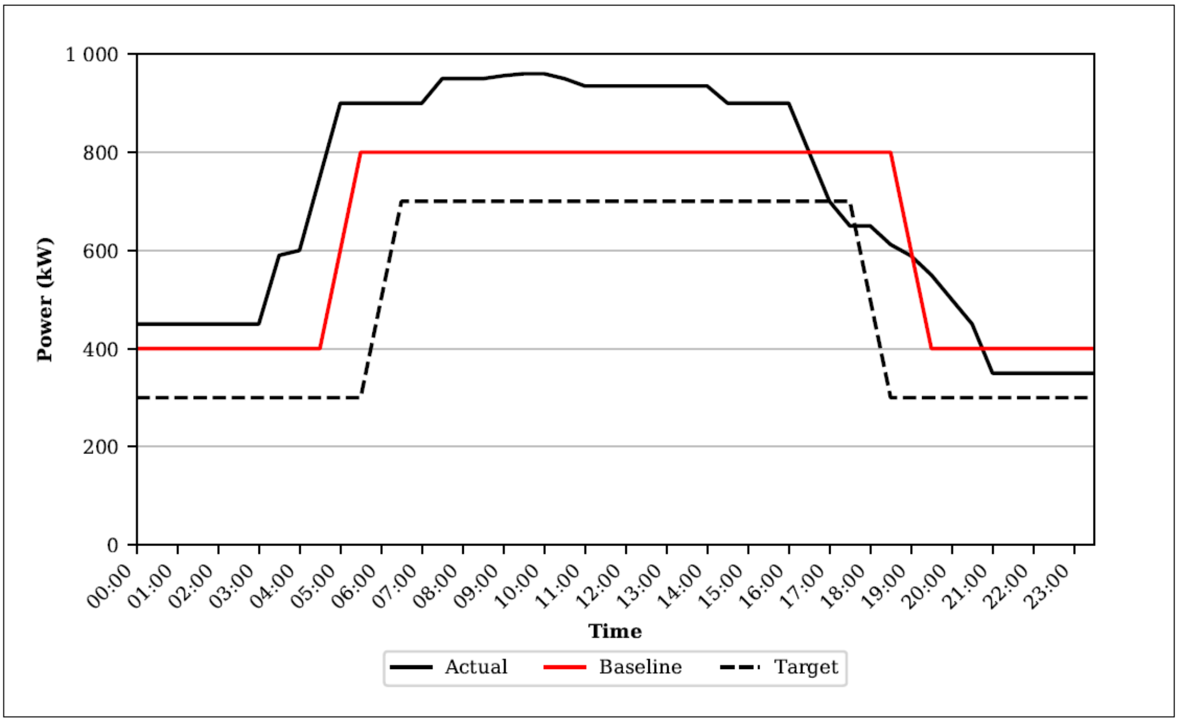

Figure 1.14: Target profile versus actual usage and baseline

Targets are often adjusted depending on ongoing system changes, whereas baselines remain constant for the same period. This is because baselines are mostly used for billing purposes. The same calculation shown on Equation 1.5 can be used to quantify the additional energy cost savings on top of the baseline using the target profile [29].

Performance adjustment

In the project life cycle, unforeseen events often occur. These events, from a deep-level mines' perspective, range from labour strikes to an increase in production. The measurement of the performance of the project will, therefore, need to be adjusted. Taking the example of a mine-wide labour strike, the overall energy usage might drastically reduce. This reduction must be excluded from or adjusted into the measurement of the project performance for increased accuracy. This can involve adjusting the project baseline in order to get a more accurate energy savings cost evaluation. The initial statistical model sample data must be changed to the data during the scaling period, such as data of energy usage within the labour strike [29], [8].

Accurate adjustment techniques give a clear image of the project performance. This has benefits in terms of transparency, as reports will not contain inaccurate information on project performance if the mine itself was not operating at full capacity.

1.2.3 Large data-set analysis in mines

As mentioned in Section 1.2.1, large amounts of data are gathered from the mines' sensors to be used for reporting and information systems. As the mines deepen and new equipment is added, the data itself increases by volume. The following sections highlight the steps taken to maintain the integrity of the data as well as methods to transmit and store it.

Database types

According to Sumathi [58], "A database is a structured set of data held in a computer, especially one that is accessible in various ways." A database ensures that the data collected is easily accessible, in an orderly manner, to an authorised user. The two main database types are the relational database and the non-relational database [58].

Relational databases store data as tables with columns and rows. Keys are associated with the relational database tables as a method to identify specific columns or rows and to facilitate fast access. The advantage of using this database type is that it is well-documented, sold, and maintained by several established corporations, which improves the efficiency of the maintenance of the database [58]. A disadvantage of relational databases is that they do not work well with semi-structured or unstructured data due to their inherent structure. This makes relational databases unsuitable for large analytics or Internet of Things (IoT) event loads [59].

Non-relational databases differ from relational databases in their structure and form. Instead of tables with columns and rows, they have collections of different categories. These collections are illustrated by documents, meaning that there can be multiple documents in one collection allowing unstructured and semi-structured data to be stored and manipulated [58].

The advantage of this database type is its schema-free nature, which allows it to manage and store large volumes of data which can then be used for analytics [59]; however, since they have no specific structure for the data stored, this makes it difficult to update the data, as you must update each detail separately [58]. For mine data logging, the relational time series database is generally used because the structure is consistent and unchanging.[6]

[6] Observation of mine data storage.

Sensor data evaluation and correction

Measuring and recording equipment often malfunction, and this results in the logging of erroneous data. There are four main types of erroneous data which can occur during the measuring and recording process, namely [8], [55]:

- **Data spike:** This is an abrupt and inexplicable change in the recorded data. It generally does not lie within the operational or realistic limits of a system and is, therefore, easily identifiable. Data spikes often occur due to equipment malfunction or the loss of communication between the recording and measuring equipment.
- **Faulty data:** This occurs when metering equipment malfunctions and reads the same static value over a period of time. This type of erroneous data is not always easily identifiable, as the recorded data can lie within the operational or realistic limits of a system.
- **Data loss:** This is identified as gaps or "skips" in the data. Data loss often occurs when the measuring and recording equipment has communication problems.
- **Inconsistent data:** This occurs when the metering equipment is labelled wrong, thereby causing a mismatch in the reported data.

These abnormalities must be addressed in order to maintain the integrity of the acquired data.

Data verification and validation

Data validation is the process of evaluating the accuracy and feasibility of data against a set of rules. This is typically performed before processing is initiated. Some examples of data validation checks include [60], [61]:

- **Type:** Checks if the data is the correct type, e.g. "name" should not be a number.
- **Format:** Checks if the data is in the correct format, e.g. dates in "dd-mm-yyyy".
- **Range:** Checks if the values in the data are within a realistic range, e.g. the hours in a day should not exceed 24.
- **Presence:** Checks if there is data entered.

Data verification is the process of evaluating if the original data matches the data entered. These methods include [62]:

- **Source data verification:** Data is manually checked against the original source.
- **Double entry:** Entering the data twice.

In order to build the baseline and target models mentioned in Section 1.2.2, the sample data must be validated and verified. Deep-level mines primarily use sensors underground for data logging, and they often are faulty. Applying these methods ensures that the models created are accurate enough to be used for baseline development.

Data transmission methods

Data can be transferred in serial or parallel through communication channels such as copper wires, optical fibres, wireless, and storage media. In the context of deep-level mines, the data from the different sensors underground is transmitted using optical fibre and more recently wireless networks [63]. This data is then sent to the data historian for storage.

Network communication protocols are used for transmitting the data from the data historian to an external source. The File Transfer Protocol -Secure (FTP/S) is the most widely used mode of transmission of data between client and server [64]. The data historian acts as the server (host) while the user requesting the data is the client. FTP/S users may authenticate themselves using a sign-in protocol in the form of a username and password. A Virtual Private Network (VPN) can be incorporated to allow a connection to the data historian from a remote location; security is not compromised, however, as another sign-in protocol is used as well as a session timeout [65], [66].

The Simple Mail Transfer Protocol (SMTP) is a communication protocol for transporting electronic mail between different hosts within the transmission control protocol/Internet protocol (TCP/IP) suite [67]. The transmitted electronic mail may contain attachments, thereby making it another method of data transmission. This can be used to also transmit the data from the data historian through an encrypted channel to the client server [64], [67].

Data security and privacy policies

Deep-level mines in South Africa have a great deal of sensitive information, such as production statistics and targets. Such information is protected by privacy policies and laws, and, as such, mines need to ensure it does not leak. External parties need to abide by the rules stipulated by the mine in terms of the access and use of the data.

The most common method mines employ in data security is securing their network outside the public network. Access into it can only be done using a VPN, which may have a session timeout for added security [28].

1.2.4 Best practice for data visualisation

Data is only as good as the way it is presented. The highlighted limitations in the present monitoring methods, such as the SCADA, included how the data is visualised. If the data is visualised well, then it becomes more readable, and conclusions drawn from it are more accurate.

According to Shneiderman *et al.* [68], there are eight guiding principles to follow when designing a user interface. These are:

1. **Consistency**: This entails that the same terminology must be used in menus, help screens, and prompts. The fonts, colours, and general layout etc. must be similar.

2. **Universal usability**: The user interface should cater for the needs of different types of users, from novice to professional. This ranges from user guides and explanations to shortcuts for experts. Both improve the perceived quality of the user interface.

3. **Informative feedback**: For every action a user performs, there must be an interface feedback to inform the user that the action was executed.

4. **Closure dialogues**: At the completion of a group of tasks, the interface must provide informative feedback. This gives users a sense of accomplishment and readies them for the next task.

5. **Error handling**: The interface should be designed to avoid user errors. Visual limitations and error handling can be employed to guide users.

6. **Reversal of actions**: Actions performed by the user should be reversible to undo any mistakes. This also encourages users to be more open to using the interface.

7. **Keep users in control**: Users need to feel that they are in charge of the actions they perform on the interface.

8. **Reduce short-term memory load**: It is recommended that user interfaces do not require that the user remember information from previous displays in order to use upcoming displays. This is because humans have limited capacity to process information in short-term memory.

When these steps are followed, the user interface can be used to its full potential.

1.2.5 Existing studies focusing on efficient energy monitoring

Several studies were conducted in relation to energy monitoring on various industries in South Africa. The studies investigated were grouped into three focus points, namely the monitoring of mining systems, benchmarking, and performance tracking. These groupings are used to identify their fulfilments and shortcomings.

Monitoring of mining systems

Studies closely related to monitoring systems in mines have been conducted over the years. Studies [25], [28], [43], [56], and [69] were done in relation to developing and utilising a generic monitoring system for mines. Goosen [25] developed a system which monitors DSM projects on mine compressed air systems. This platform only monitored compressed air energy usage and did not extend to other mining systems.

Van Jaarsveld [43] developed a system which primarily focused on the condition of the mine system machines. It was efficient in monitoring when the machines required repair. Energy usage management was, however, not addressed in the system.

Du Plessis *et al.* [69] developed a system which directly communicates with the SCADA for the real-time monitoring of cooling systems. This system was primarily based on mine cooling systems and, therefore, did not account for the other mining systems, such as compressed air and refrigeration.

Du Plessis [28] primarily focused on the monitoring and maintenance of energy management systems deployed on remote site locations. It did not focus on the energy usage of the systems, but provided a guide on how to design remote communication systems.

Van Rensburg [56] developed a web-based information system to monitor the performance of projects on deep-level mines. It provided key insights on how to develop information systems which do not overwhelm users; however, this information system was developed for reporting on past events. It lacked the ability to track problems as they occurred.

Benchmarking

Studies [70], [71], and [72] were mainly focused on the benchmarking and energy management of the monitoring mining systems.

Zietsman [70] primarily focused on a strategy to identify financial scope for implementing projects on cooling systems. Although its primary objective was not monitoring, it provides useful insight in terms of implementing modelling strategies.

Al-Chalabi [71] focused on a “bottom-up” approach to a sustainable method for benchmarking energy usage in refrigeration systems. The approach was generic enough and can potentially be applied to the other mining systems where monitoring is needed.

Ploennigs *et al.* [72] developed a real-time system to diagnose, monitor, and forecast smart building energy usage. This study is not focused in the mining industry; however, the fundamentals in the modelling and design of the monitoring applications can be applied to an information system directed at the mining industry.

Performance tracking

Botma [73] focused on the development of a software platform which is used to manage projects. It is a task-based information system which is used to track performance. Although it is not primarily based in the mining industry, it has adequate information pertaining to exceptional user interface design, which was a flaw identified in the SCADA.

Fockema [24] developed a web-based reporting system which reported on mine energy usage. This study highlights the importance of displaying the right amount of data without straining the user. It can be further improved upon by using these visual techniques on a real-time platform.

Sartor *et al.* [41] provided general recommendations to help select or customise the energy elements or parameters of a high-performance computing data centre infrastructure dashboard. It highlighted the importance of certain key indicators which are important for efficient energy management of data centres. Although this study was not focused in the mining industry, the strategy used to develop the user interface is generic enough to be applied in other industries.

Summary of evaluated existing studies

Expanding on the already established research topics pertaining to energy monitoring systems in the mining industry the final study focus topics are as follows:

- The development and use of a monitoring system.
- Benchmarking and performance tracking.
- Energy management principles.
- Optimised interface design.

The aforementioned studies contain individual strengths; however, when looking at a more holistic monitoring method for all mining systems, they fall short.

Table 1.3 visually summarises the research done with fulfilments and shortcomings. "Yes" indicates that that study did work on the given study focus, and "No" indicates that the study did not include the aforementioned focus.

Table 1.3: Gaps in existing studies

Source	Monitoring Systems	Performance Tracking	Energy Management	Optimised Interface
[25]	Yes	Yes	Yes	**No**
[28]	Yes	**No**	**No**	Yes
[70]	**No**	Yes	Yes	**No**
[43]	Yes	Yes	**No**	**No**
[56]	Yes	**No**	**No**	Yes
[71]	**No**	Yes	Yes	**No**
[73]	**No**	Yes	**No**	Yes
[24]	**No**	Yes	**No**	Yes
[41]	Yes	**No**	**No**	Yes
[72]	**No**	Yes	Yes	**No**
[69]	Yes	Yes	Yes	**No**

As shown, a gap exists between the use and development of a mine energy monitoring system and an optimised interface design. This study aims to fill the gaps and provide a more complete solution to efficient energy monitoring in the mining sector.

1.3 Need and objectives

Problem statement: Owing to the limitations in present mine monitoring systems, energy-wastage events are not detected and mitigated in time.

As addressed from literature and the studies mentioned on Table 1.3, the need exists to develop a system which can efficiently monitor mine energy usage and display it in a simplified manner to promote quick response. This will help in the tracking and stopping of energy-wastage events as they occur in order to maintain the cost savings in implemented projects. This intervention will also help in reducing the overall deterioration of implemented projects over time.

The proposed monitoring system should also aid monitoring personnel in:

- Measuring the impact of actions in terms of the utilisation of the systems.
- Reducing the strain of overwhelming raw data.

Specific objectives have been identified in order to achieve the end-goal. These objectives can be divided into two sections, namely technical and user engagement objectives.

Technical objectives

1. Develop a procedure for the implementation of a statistical model for accurate baseline and target profile creation. The profiles should be easily updated and recalculated.
2. Implement the targets on a visual platform and SMS notification system.
3. Validate the method through:
   - Applying the system to monitor different project types.
   - Tracking and stopping energy-wastage events as they occur.
   - Evaluating the performance of a project over a set time for deterioration.

User engagement objectives

1. Promote user engagement by reducing the strain caused by present inefficient monitoring systems.

1.4 Dissertation overview

- **Chapter 2: Development of the solution** – In this chapter, the user requirements and design specifications of the proposed monitoring system are identified. A generic method is developed to create baselines and targets which will be used on the visual platform and SMS notification system. This chapter also includes the design steps for the visual platform and SMS notification system.
- **Chapter 3: Results and validation** – This chapter discusses industry case studies where the monitoring system was implemented. This is to demonstrate the impact of the monitoring system in stopping energy-wastage events as well as promoting good user experience. The study is also evaluated to ensure that it addresses the objectives and goals stipulated in Section 1.3
- **Chapter 4: Conclusion** – Conclusions are made regarding the effectiveness of the monitoring system based on the results discussed in Chapter 3. Limitations as well as recommendations for future work are discussed.

Chapter 2

Development of the solution

2.1 Preamble

This chapter is an overview of the steps taken for the implementation as well as the design of the proposed monitoring system developed in order to address the limitations identified in Section 1.3. It will detail the methods used to solve both the technical and user engagement objectives.

The proposed monitoring system has three main functional parts, namely:

- A performance tracker.
- A user interface (web-based platform).
- A notification system (SMS).

The proposed monitoring system has two main process flows which comprises:

- The setup of all three functional parts.
- Daily operation.

The literature discussed in Section 1.2 will form the base requirements for each of the three main functional parts of the proposed monitoring system. These requirements will affect the overall implementation and design of each. The performance tracker will provide analytical solutions in the form of baselines and targets and will be implemented on an existing ESCo web-based platform as the user interface and on a standalone SMS notification system. The steps taken to design each of the functional parts of the system are shown in the following sections.

The setup process is performed when a new project is added to the system or when alterations are being made to existing projects. It involves four main steps:

- **Step 1:** The acquisition of data. The historical data sample is acquired in order to be used for the performance tracker.
- **Step 2:** The sample data is prepared. Data validation and verification is performed.
- **Step 3:** Initial baselines and targets are generated using the historical data sample.
- **Step 4:** The systems which are being actively monitored are added to the user interface and SMS notification system.

The daily operation process involves the monitoring system interacting with live data and can be summarised in three main steps:

– **Step 1:** The acquisition and transmission of data.

– **Step 2:** Quick data preparation.

– **Step 3:** The live data per system is processed and compared to the baselines and targets for the user interface and SMS notification system.

The system is developed using the rapid application development methodology as illustrated on Figure 2.1. Table 2.1 shows the main tasks during each development cycle, and a detailed breakdown of each follows. Employing a structured approach will ensure that the implementation and design of the proposed monitoring system is successful.

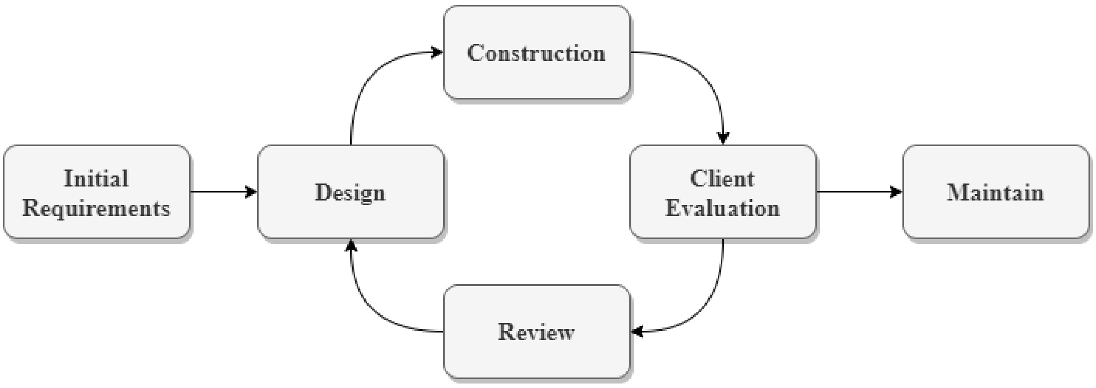

Figure 2.1: Rapid application development methodology

Table 2.1: The breakdown of different phases

Initial requirements	**Design-evaluation loop**	**Maintain**
1. Focus on main mining systems	1. Performance tracker 2. User interface 3. Notification system	1. Client feedback

– **Initial Requirements:** The main mining systems discussed in Chapter 1, such as compressed air and pumping, are grouped. From the groupings, implemented existing projects are evaluated in order to establish the needs in terms of improving the project performance.

– **Design-evaluation loop:** In this phase, the established requirements are addressed through a three-part system, namely the performance tracker, the user interface, and the notification system. The system is designed and evaluated through an iterative process to ensure that it is effective in addressing the recognised problem.

– **Maintain:** The three-part system is continuously maintained with feedback from the client.

2.2 System requirements

The main mining systems which fall under the initial requirements of Table 2.1 are the high energy users. These are selected on the basis that they show the greatest impact in terms of energy wastage and have the greatest saving recovery if incidents are detected on time.

The main design specifications for the proposed monitoring system are selected in accordance with the technical and user engagement objectives listed in Section 1.3. In order to track the unwanted energy-wastage events effectively, the monitoring system must notify users promptly without overwhelming them. This will be achieved with the help of accurate baselines and targets and by following the best practices for data visualisation discussed in Section 1.2.4. Table 2.2 summarises the design specifications in detail per functional part.

Table 2.2: Monitoring system specifications

Specification	**Description**
1. Performance tracker	
Baseline/target creation	Targets and baselines should be created using custom data samples. Calculations on the samples given the adjustments should be possible.
Model re-evaluation	Implemented baselines and targets should be flexible enough to be re-evaluated and calculated depending on external changes.
2. SMS notification system	
Notify users	Linked users should be notified on energy-wastage events on their mobile devices.
Avoid overloading users	Notifications sent should not overwhelm the recipients.
Post-analytical auditing	A history of all notifications sent out should be available for post-analytical auditing to quantify the notification trigger frequency.
3. User interface	
Display data	The power usage data of the main mining systems should be displayed in a simplified manner.
Impact measurement	Additional metrics should be used to quantify the energy data into more simplified quantities.

For the overall system interaction, the specifications are as follows:

Reaction speed

The system should process all the inputs and give outputs to the user interface and notification system in a short space of time. This ensures it plays a vital role in stopping the wastage of energy.

Measurement of impact

The system should provide vital information which will engage the users in a simplified form, either energy consumption or energy cost, to enable a sense of responsibility.

User-friendly experience

The user interface and SMS notifications must give the user a less straining experience compared to using the SCADA. Cognitive overload must be reduced as far as possible in order to limit the time taken to understand the message brought across. Potential problems must be easily identified and rectified.

2.3 The acquisition of usable data

Reliable data is needed in order to develop a useful benchmarking and monitoring tool. Historical data will be used for the initial model development, and the live data will be used for the general operation of the monitoring system. This section shows the steps taken to acquire usable data for the analysis and model development as well as the daily use.

2.3.1 Data extraction methods and systems

Reliable data is needed for the constant operation of the proposed monitoring system. Figure 2.2 illustrates a simple flow diagram of how metering data is gathered from the underground devices (PLCs) and then transmitted first to the SCADA and then to a data historian. This process is automated and requires no user input. The HMI, as mentioned in Section 1.2.1, is only used to override control operations.

As discussed in literature in Section 1.2.1, the SCADA has a direct connection to the devices underground using communication protocols such as OPC, DDE, and Network DDE. This means that the information logged is displayed instantaneously. The SCADA also has a direct two-way connection to the data historian/database, as illustrated in Figure 2.2, which then allows it to trend historical data. When extracting this data to an external application, the ideal method in terms of reducing latency is a direct connection through the SCADA to the PLCs themselves; however, this gives rise to incompatibility problems, as the different SCADA communication protocols will have to be considered in the design. A generic method that can overcome this incompatibility and provide a universal solution will, therefore, need to be implemented.

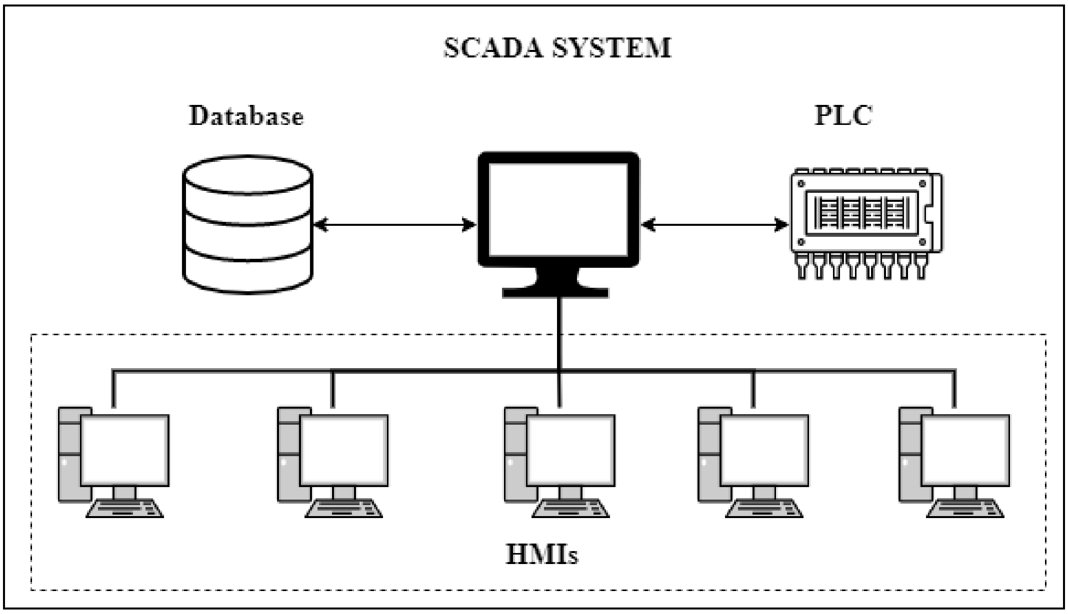

Figure 2.2: Data acquisition flow diagram

A solution to overcoming the incompatibility to acquire the required data is to extract it from the data historian; however, latency is introduced between the logging and storage of the data. Structured Query Language (SQL)-based queries are used to continuously extract the data in specified intervals to provide approximate real-time processing. The extraction parameters are selected based on the following factors:

- Metering logging intervals
- Data storage intervals
- The amount of data

The selection of the most suitable extraction as well as data interval is calculated using Equations 2.1 and 2.2.
The data extraction interval is summarised by the following equation:

$$I_E = T_{Log} + PLC_{Log} + Delay \tag{2.1}$$

Where:

I_E = the data extraction interval
T_{Log} = the time it takes for the data to be packaged and transmitted
PLC_{Log} = the fixed data logging intervals of the PLCs
$Delay$ = the time delay allocated for latency

The data interval is summarised by the following equation:

$$I_D = 2 \cdot I_E \tag{2.2}$$

Where:

I_D = the fixed data interval
I_E = the data extraction interval

The most suitable lowest extraction interval, as shown on Equation 2.1, is when the PLC and transmission has clocked at least once with the inclusion of a small delay. The most suitable lowest data interval, as shown on Equation 2.2, is two times the extraction interval. The aim is to reduce latency as greatly as possible while limiting the amount of duplicate data extracted and transmitted to provide better efficiency.

2.3.2 Data transmission methods and systems

Section 1.2.3 provided the different methods to transmit data from the remote server to the client. For the proposed monitoring system, the data needs to be continuously transmitted to approximate the desired real-time operation. To achieve this, the FTP/S can be used to continuously transmit the data from the remote site; however, as previously mentioned in literature, a VPN with a session timeout is often incorporated when dealing with remote access to the mining systems. This interruption would have a negative impact in the flow of data, as it will be lost during the session downtime.

An alternative method is the use of a mail server as a data transmission method as discussed in Section 1.2.3 and illustrated on Figure 2.3. There is no direct link between the data historian and the client. Data extraction software is set up within the secure mine network, thereby forfeiting the need for a VPN connection. The extracted data is then packaged and emailed to the client. On the client side, the email attachments are translated, and the extracted data is stored in the client's database. The advantage of using this method versus the direct connection is that there are no scheduled interruptions. If interruptions do occur, the data will not be lost, as it is will be pending on the mail servers.

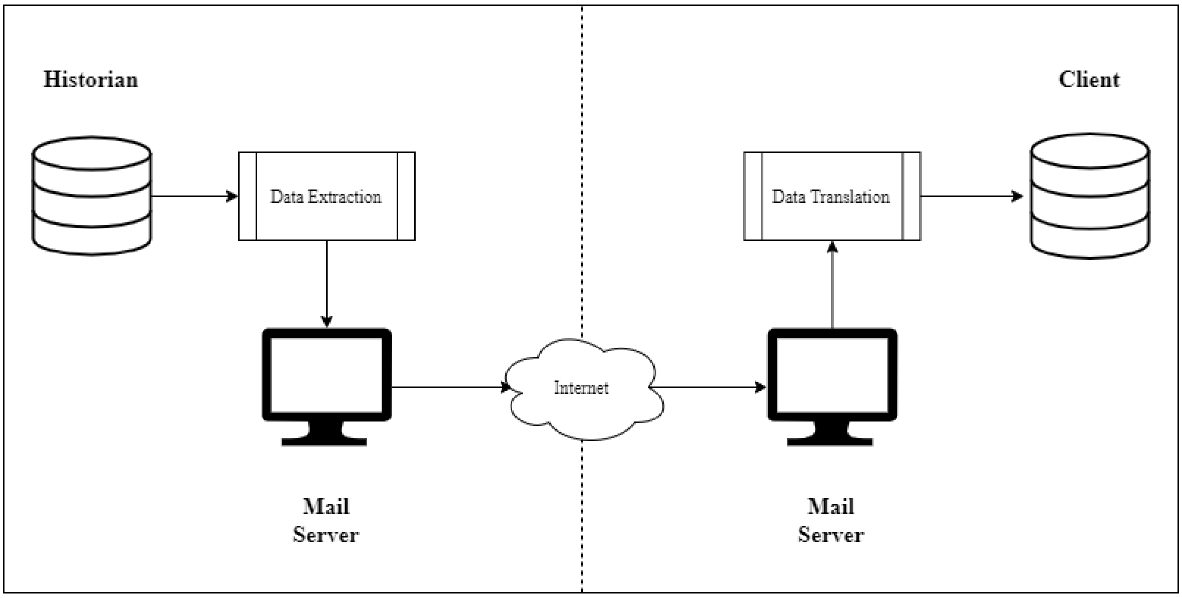

Figure 2.3: Data extraction using SMTP

2.3.3 Data structure

The data historian is often used to store mine energy data as a time series database.[7] This means it is optimised for storing and serving data as timestamped data points. Table 2.3 shows an example of the data structure of the data historian. Each PLC or sensor underground is allocated to a tag(metadata)[8] for easier data storage. Queries are used to extract data according to the "Tag" and "Date Time".

Table 2.3: Data historian example

Date Time	**Tag**	**Value**
2020-05-11 00:30:00	Tag 1	2500
2020-05-11 00:30:00	Tag 2	4582
2020-05-11 01:00:00	Tag 1	5612
2020-05-11 01:00:00	Tag 2	5184
2020-05-11 01:30:00	Tag 3	1625
2020-05-11 01:30:00	Tag 4	23

A single mining system such as compressed air or pumping may contain more than one tag linked to it. This signifies that before a system can be monitored, the different tags will need to be grouped. For example, a compressed air system might contain four compressors, so to monitor their power consumption, the individual tags are grouped and the values are summed up. The total summed value will then be monitored as the system itself.

[7] Observation of the mine data historian

[8] In information systems, a tag is a keyword or term assigned to a piece of information. Source: https://en.wikipedia.org

2.3.4 Data quality assurance procedure

Vigorous validation is performed for the data used for the model design as it is needed to create accurate baseline and target models. Data preparation is performed in the following order:

1. **Filtering and grouping:** The data is filtered and grouped into desired smaller subsets. This makes it easier to process as well as to find discrepancies. An example of the grouping of power meter data is separating the data into the different mining systems such as ventilation, water reticulation (pumping), compressed air, etc.

2. **Matching filling type:** Time-based data logging is averaged by using either previous timestamps or upcoming timestamps. For example, time-based data which is in 30-minute intervals can be averaged as follows: the data value for 08:00 will either be an average of the 07:30 to 08:00 timestamps or 08:00 to 08:30 timestamps. This is formally known as forward filling and backward filling. In order to prepare the data accurately for analysis, the filling types should match.

3. **Data validation:** Data validation techniques discussed in Section 1.2.3 are performed. The exact validation techniques performed are type, format, range and presence checks. Once these checks are completed the data is ready to be processed and modelled.

For the data used for the daily operation real-time monitoring, quick validation techniques are performed. Range checks are not performed, as they can expose unusual data trends which stem from faulty equipment.

2.4 Performance tracker development

This section discusses the steps taken to develop and set up the performance tracker. These steps are only initiated after accurate and adequate preparation of the historical data is performed. Furthermore, this section addresses Point 1 of the technical objectives listed in Section 1.3.

2.4.1 Generic model

Figure 2.4 illustrates the generic flow diagram of the performance tracker. It contains three main stages, namely data import, processing, and data export. Each stage is executed consecutively. A summary of the stages follows.

Data import

This is the first stage initiated when utilising the performance tracker. When the process of preparing the historical power data is completed, the data is then used as the initial input for the performance tracker. For continuous improvement and re-evaluation, the input of the performance tracker then becomes the output with adjustments set. Implementing these adjustments is referred to in literature as performance adjustment. It can be an adjustment due to an increase in production or accounting for labour strikes which may occur.

Data processing

This step involves scaling the power profiles according to the given adjustments and calculation type. When the energy-neutral calculation is selected, it uses the adjustments as the scaling reference for the entire profile. The overall power profile is maintained but the amplitude is shifted depending on the given adjustments.

When the time-based calculation is selected, a further input, time frame, is needed to complete the process. An example of such a time frame is the Eskom ToU discussed in Section 1.1.3, namely “peak”, “off-peak”, and “standard” times. The adjustments given will, therefore, only be applied to the desired time frames. The profile outside the adjusted time frame will remain unchanged.

Data export

When either the time-based or energy-neutral calculation is performed, the resulting profiles are then exported as data sets which are used by the user interface and SMS notification system. These data sets are in the same format as the imported data set to allow for the readjustment mentioned in the Data Processing step.

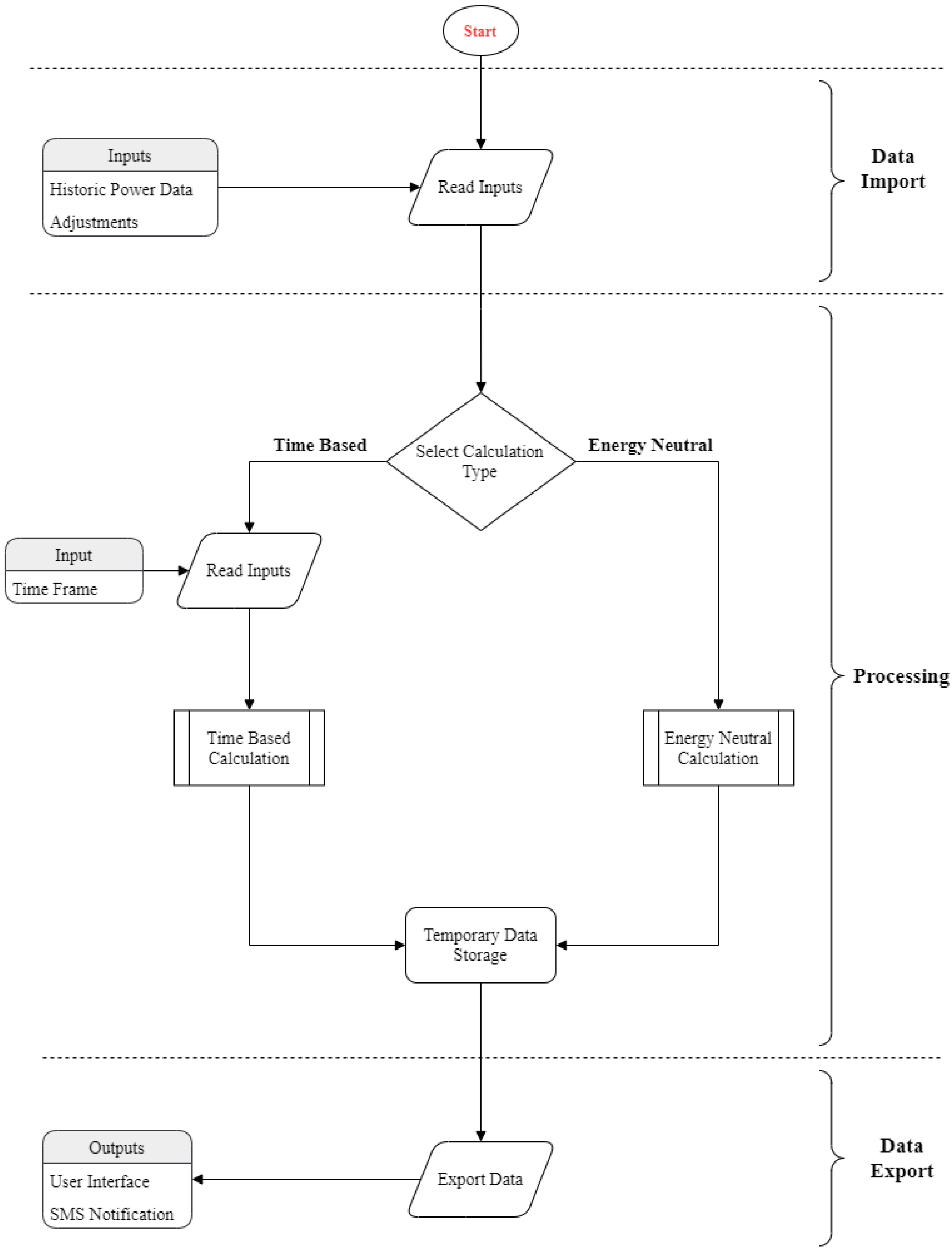

Figure 2.4: Performance tracker generic model flow

2.4.2 Baseline profile

As mentioned in Section 1.2.2, the most important step in energy planning is establishing an energy baseline. Figure 2.5 illustrates the process flow for the development of the baseline model and profile.

Assessment period selection

As mentioned in literature by [50], when creating the baseline, the data group (time period) and high energy using systems must be identified first. Since the purpose of the proposed monitoring system is to mitigate energy wastage on implemented projects, [50] can be used to find the most suitable time period for analysis.

Model selection

Section 1.2.2 highlighted the different types of baseline models which can be used for energy management. For this proposed monitoring system, only the energy consumption will be considered; therefore, the regression baseline model is not considered because of the nature of the implemented projects. The most optimum model to use in this case will, therefore, be a combination of the energy-neutral and constant baseline model, as future adjustments will be made in the target profile.

Data preparation

This step involves ensuring the data supplied is accurate for modelling. This uses the steps discussed in Section 2.3.4, namely filtering, grouping, matching fill type, and validation. This step is needed to remove the outlier values as well as identify gaps in the historical data.

Baseline correction and evaluation

The evaluation of the developed baseline is an iterative process where the main purpose is to prove the feasibility of the model developed. This involves comparing the developed baseline with the present project performance. A baseline can be found to be unfeasible if the comparison reveals considerable discrepancies. These discrepancies can be in the form of baseline values being too low or too high to be realistically attained within the project scope. This will prompt a secondary check. This secondary check identifies the source of the problem, whether it is with the data preparation or with the entire data sample.

Problems with data values can be in the form of data spikes or negative values. Reapplying the data quality check procedure mentioned in Section 2.3.4 will aid in rectifying the problem, and thus the baseline can be recalculated. If the problem lies within the chosen data sample itself, the entire process must be restarted. This will ensure the accuracy of the model.

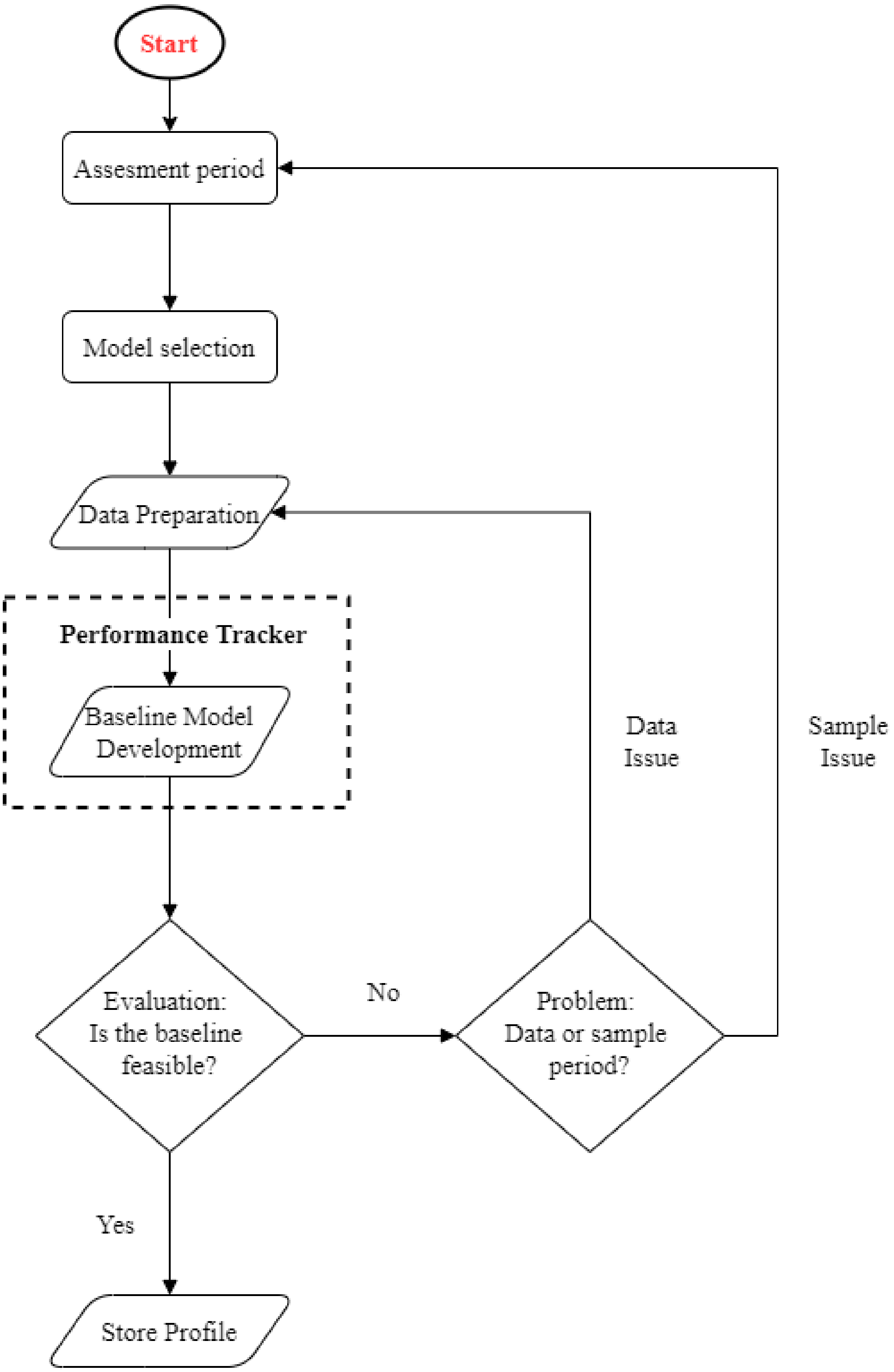

Figure 2.5: Baseline model development flow diagram

2.4.3 Target profile

The target profile is developed after the baseline model has been finalised. The target profile includes additional inputs which are caused by the constant environmental change of the mine or simple adjustments caused by unforeseen events. Ideally, when this step is initiated, no further changes are made on the baseline, as it will be used for billing the ESCo based on the performance contract. The target then becomes the metric for additional energy savings. Figure 2.6 illustrates the process flow of the target model and profile development.

Target adjustments

The initial target adjustments can be either cost saving goals or operational changes. These values are input into the performance tracker together with the calculated baseline model.

Target correction and evaluation

Much like the baseline, the target model is also evaluated to prove its feasibility. This ensures that the targets set out can be met and are realistic. If the target is found to not be feasible, the adjustment values are refactored, and the target profile is recalculated in the performance tracker. This evaluation loop is performed until the target satisfies the desired needs.

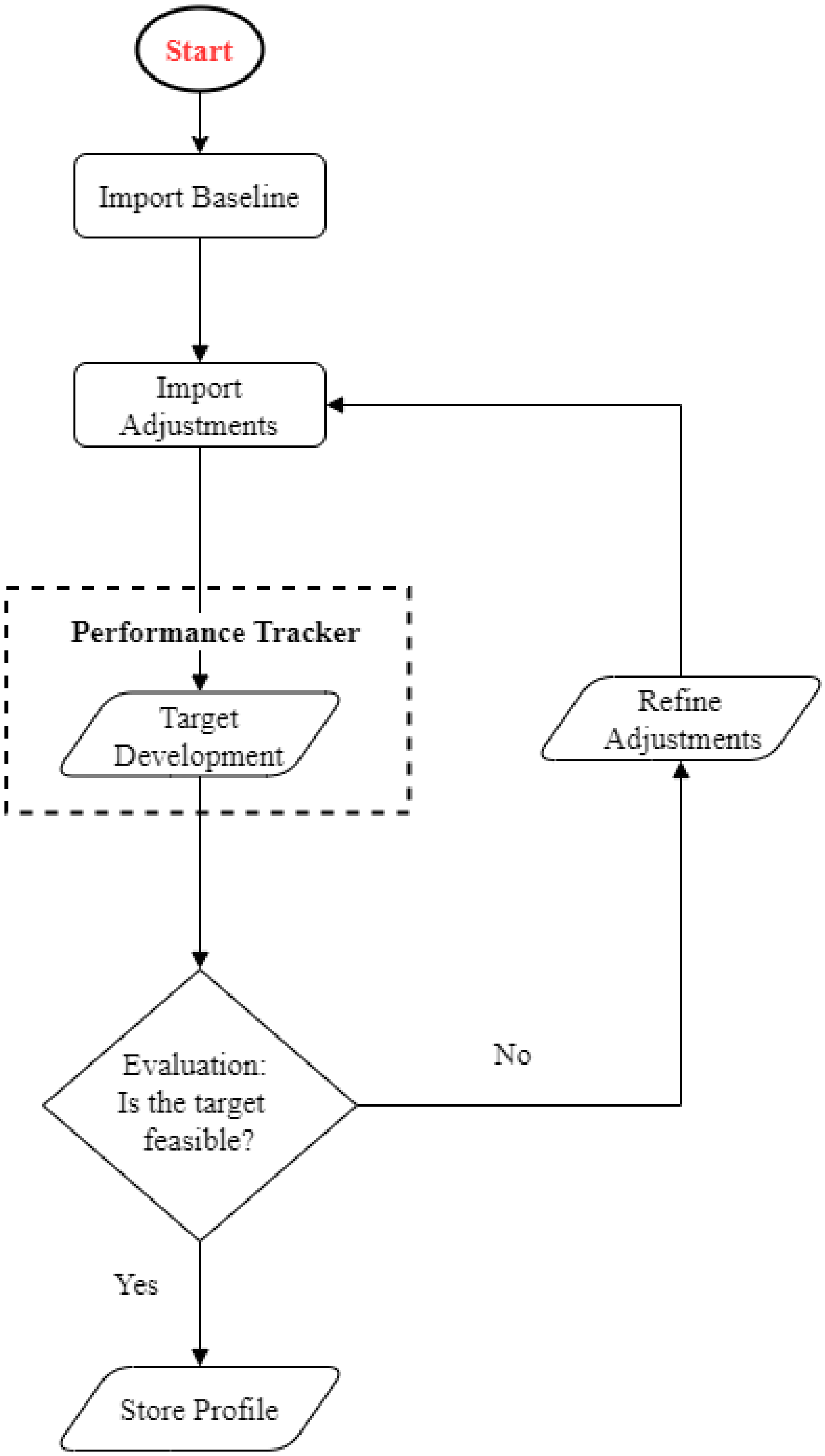

Figure 2.6: Target model development flow diagram

2.5 Implementation of the performance tracker

This section discusses the performance tracker implementation and addresses Point 2 of the technical objectives listed in Section 1.3. After the targets and baselines are calculated, the outputs are used in two forms: as an SMS notification system, and as an optimised user interface.

2.5.1 SMS notification system design

Figure 2.7 illustrates the design structure of the SMS notification system. The performance tracker outputs or profiles are input into the notification system as the **Notification Value**.

When setting up the notification system, three main components, illustrated on Figure 2.7 as numbered circles, must be defined. These are the notification description (1), the reference tag database (2) and the calculations (3). All the remaining processes are dependent on the three main components.

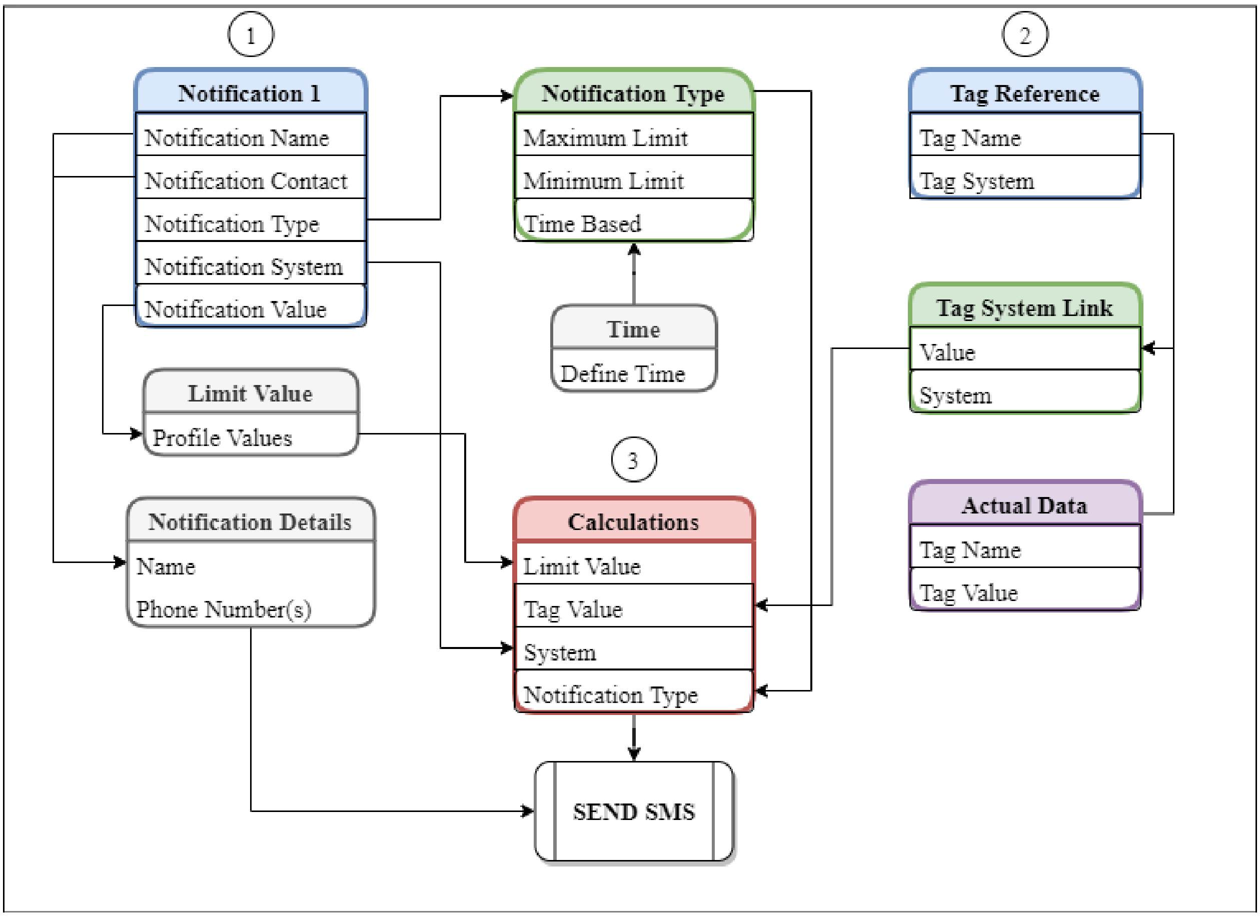

Figure 2.7: SMS notification system design structure

Description of the notification

Each notification has five main fields, namely:

1. **Name:** This is the name given to the notification which describes the mining system it reports on.
2. **Contact:** These are the contact details of the person responsible for monitoring the mining system.
3. **System:** This is the unique key which links the notification system to the correct referenced tags.
4. **Type:** This is the notification type which affects the calculations performed; it can either be value- and time-based or only value-based.
5. **Value:** This is the numeric value within the profile which will trigger the notification. These values are direct outputs from the performance tracker.

Each notification is individually described to prevent duplication.

Definition of the reference database

The reference database contains a list of tag names which correspond to specific mining systems. When the reference is set up, it is used to categorise the extracted data into the system and the value. This pair is then passed onto the calculations. Only tags stored in the reference database will be used in the notification system. The **Actual Data** step illustrated on Figure 2.7 will contain more data than is currently needed. The reference database is primarily used to filter out unwanted information, thereby making overall system processing much faster.

The development of calculations

The calculations are based on the notification type selected. The two main types of calculations are the time-based and non-time-based. The calculation compares the notification system value with the system value received from the live data. For the non-time-based calculation, the result is used to trigger the notification if it falls below or above the specified minimum or maximum limit.

The time-based calculations only trigger if the actual data falls within the specified time. For example, a load shift notification will only trigger if the extracted data timestamp is within the ToU peak time frames. If the data falls outside the time, the calculation is halted. Once the calculations are performed the notification is only triggered if the minimum or maximum limit was exceeded.

Promoting user engagement

As mentioned in literature, when using mobile notification applications, user engagement must be considered. Keeping the message concise helps the recipient promptly perform the required task. When considering user engagement, the structure and frequency of the notifications was defined.

Figure 2.8 is a snippet of the output of the SMS notification system. It is designed to promote user engagement by ensuring that the message is as concise as possible by displaying only the vital information. This vital information is summarised as the following four items:

1. **Date time:** This is the date and timestamp of when the energy wastage incident occurred.
2. **Notification name:** This is used as a description of the project being monitored so that the recipient knows which systems are linked.
3. **Notification limit:** This is the trigger value which is the performance tracker output.
4. **Actual value:** This is the value of the sensory equipment logged in the data historian.

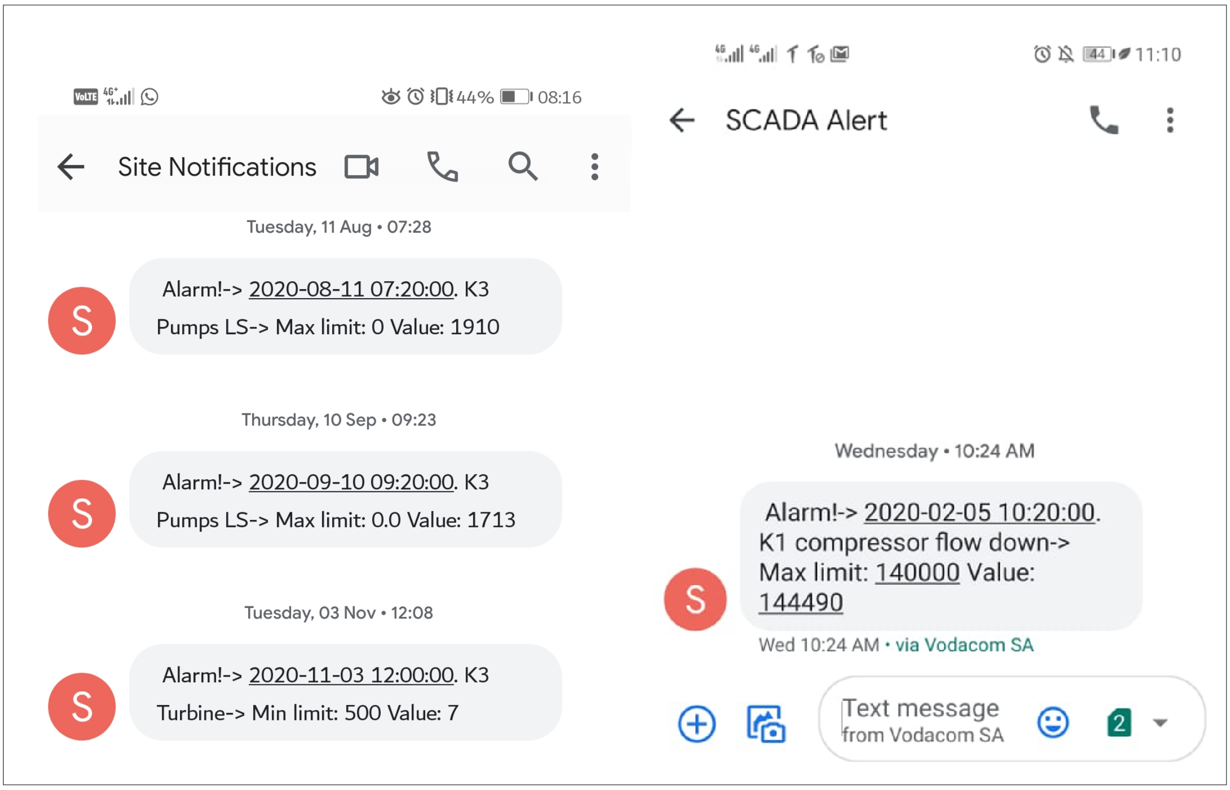

Figure 2.8: SMS notification system output

The recipient will immediately know which system is faulty and by what quantity. By having a simple structure, the SMSes ensure that the recipient of the notification will find it much easier to understand the message and is less likely to perceive it as insignificant.

The frequency of the SMS notifications plays a vital role in promoting user engagement, as it will affect their perceived usefulness. The notifications are set up to only trigger once a day for the value-only-based calculations. For time-based calculations such as load shift projects, the notifications will trigger for both the morning and evening peak times. This creates importance in the message.

Each notification sent is logged daily in order to provide post-analytical results. The following section details the logging structure of the SMS notifications.

Notification event logging

A track record of each notification triggered and sent is stored and later used for auditing. Figure 2.9 is a snippet of the SMS log file structure. Each log file is compiled per day to make it easier to filter different date periods.

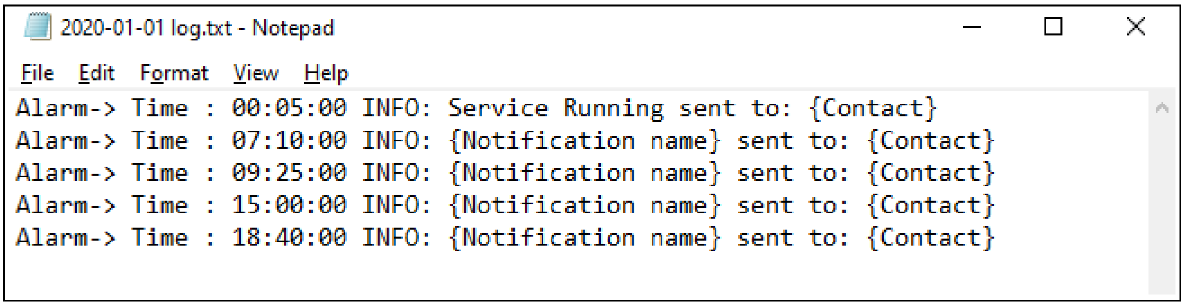

Figure 2.9: SMS notification system log file structure

The structure, as illustrated on Figure 2.9, follows a similar convention to the actual notifications being sent out. Each log file contains three main items, namely:

1. **Time:** This is the timestamp of when the SMS was triggered.
2. **Notification name:** This is the description or short name of the project being monitored.
3. **Contact:** The recipient and responsible person(s) to rectify the incident.

The first item logged is the "Service Running" SMS. This notification is primarily used as a diagnostic tool to identify instances when the notification system was inactive. The logs can be analysed to evaluate the feasibility of the implemented targets. If a notification is triggered multiple times, it is possible that the targets implemented are not feasible, and thus a readjustment is needed.

2.5.2 User interface design

The user interface is embedded on an existing ESCo's web-based platform for easier implementation because the framework has already been established. The outputs of the performance tracker are used as the target profiles for monitoring.

The structure of the user interface

Figure 2.10 illustrates the data flow for the user interface from the data transmission step. The data which is transmitted from the remote site is then translated and stored in the ESCo database. The user interface is directly linked to the ESCo database to acquire two key items, namely:

1. The desired structure of the user interface through a tag reference.
2. The actual and target data to be trended on the user interface.

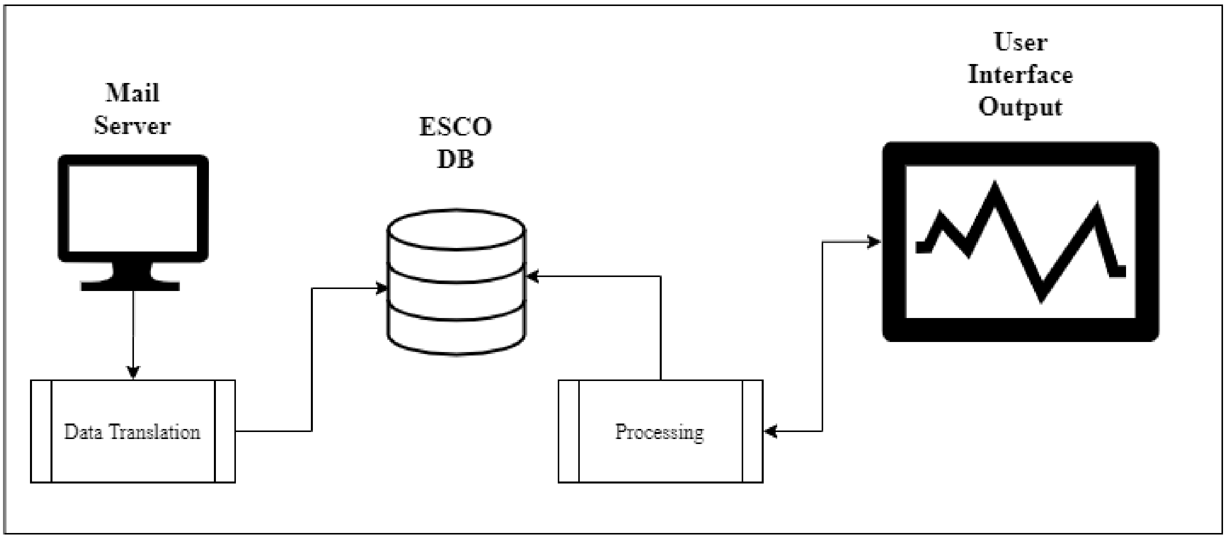

Figure 2.10: User interface data flow

Setup of the user interface

Figure 2.11 illustrates the design structure of the **Processing** step presented in Figure 2.10. The systems denoted as **System A, System B, and System C** represent the main mining systems discussed in Section 1.1.2, namely compressed air, pumping, ventilation, etc. To begin the setup, the mining systems which need to be monitored are determined by linking the available live data tags they belong to.

Once the systems have been established, the target profiles which are the calculated outputs of the performance tracker are linked. Once all the linking is completed, the continuous process begins. The interface continuously updates as new live data is received from the mine and is trended accordingly.

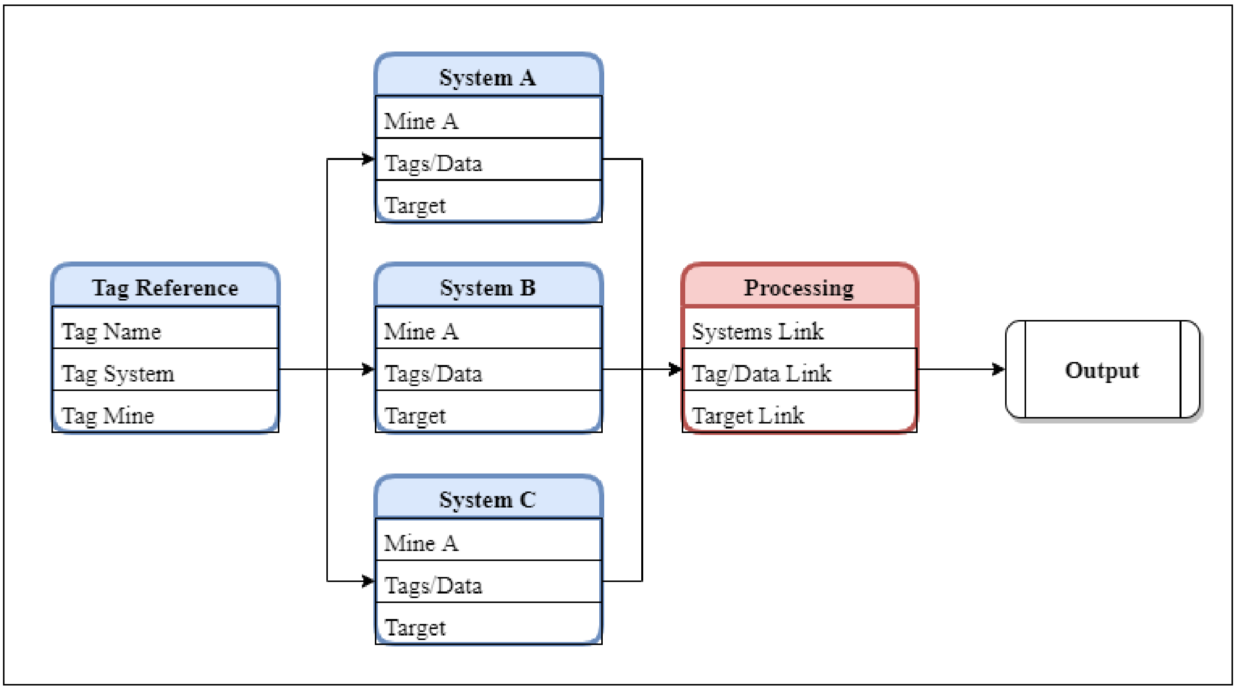

Figure 2.11: User interface setup

Designing for a user-friendly experience

The visual design of the user interface closely follows the best practices used in [68] and discussed in Section 1.2.4. Simplifying the SCADA and reports is the first step. According to literature, the SCADA has a problem with overwhelming the user with too much information. To overcome this, the user interface is simplified to only show the main mining systems. This is illustrated on Figure 2.12.

When setting up the bar charts, the user selects which of the main mining systems need to be monitored, depending on the scope of the projects implemented. This narrows the focus down and eases the implementation. As illustrated on Figure 2.12, at a given instance of time, the yellow bar denotes the actual usage, and the red bar denotes the targets calculated from the performance tracker. The user of the system must now only focus on reporting the systems which have the actual (yellow) bar longer than the target (red), which means the usage must be reduced.

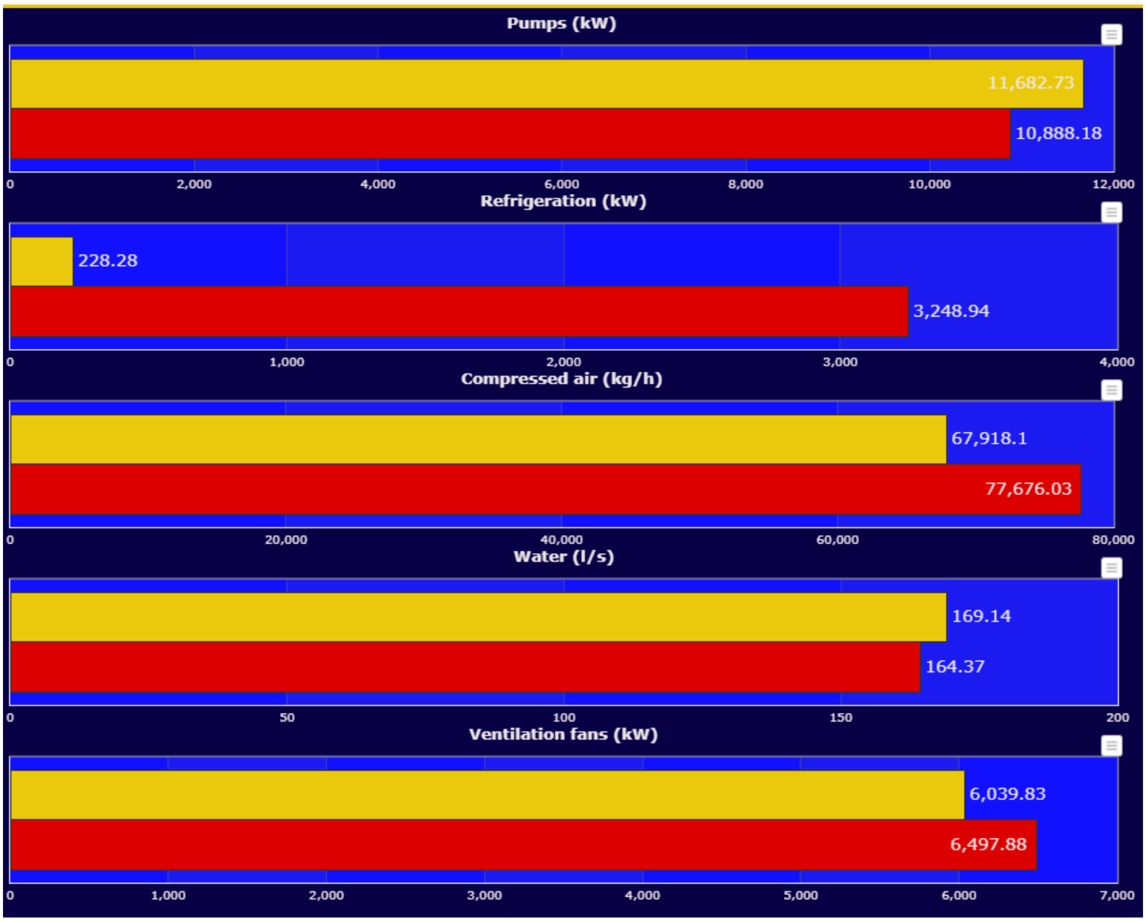

Figure 2.12: User interface target versus actual bar chart

An additional limitation indicated in literature was addressing the impact of actions. The control operators and monitoring personnel who use the SCADA system are often unaware of their impacts in terms of reacting to energy-wastage events in a timely manner. Figure 2.13 illustrates a line chart which translates the actual and target profiles into cost graphs. The line chart also incorporates the electricity tariffs previously mentioned in Chapter 1 indicated by shading the background to give an accurate measurement of the costs incurred during the day due to energy wastage.

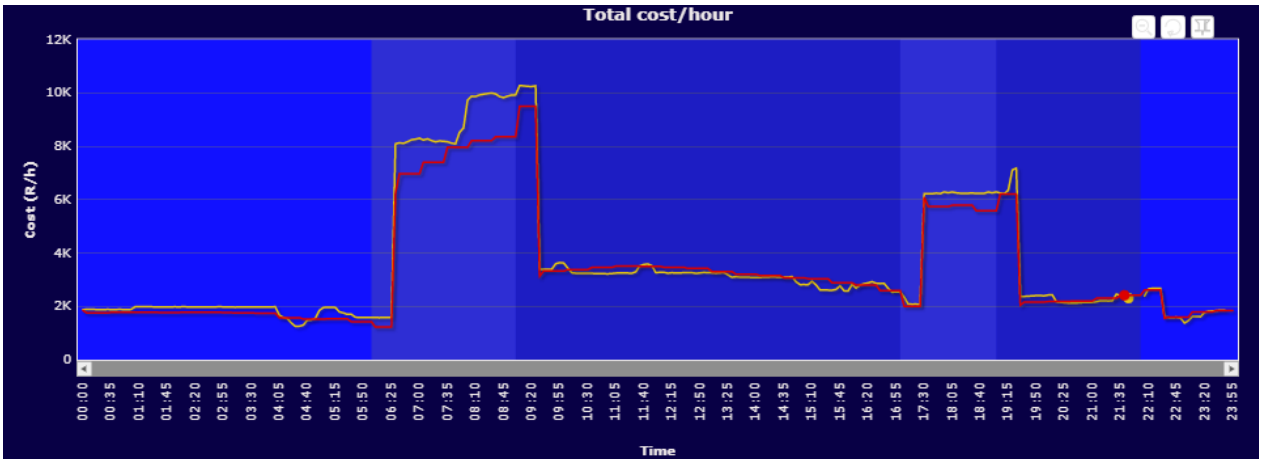

Figure 2.13: User interface daily cost per hour line chart

Figure 2.14 illustrates the cumulative cost line chart per day. It is derived from summing the cost–incurred–per–hour graph. In simple terms, the user of the system should aim to keep the actual line (yellow) below the target line (red) in order to maintain savings. This gives the users a sense of responsibility because energy values are converted into a more relatable quantity - money.

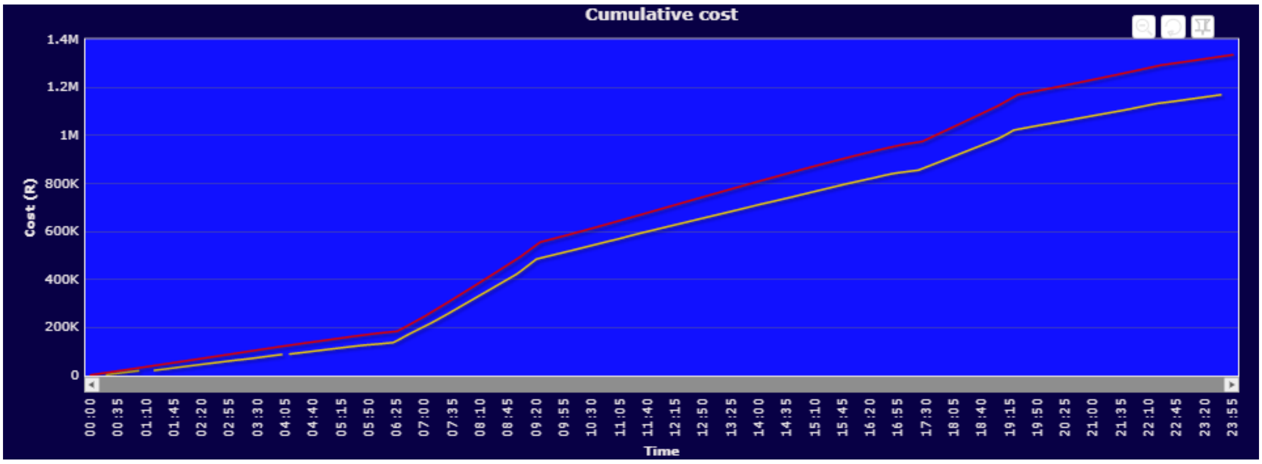

Figure 2.14: User interface cumulative cost line chart

To once again solve the problem of having too much information in the SCADA and reporting, an overview page is designed. Figure 2.15 illustrates an overview page which can be used by users who monitor multiple mining systems at once. As illustrated, the mining systems are placed in block form and the calculations are performed in the background to give the output shown. Table 2.4 shows the legend for the overview page. With this view, multiple systems on different mining shafts can be monitored with ease.

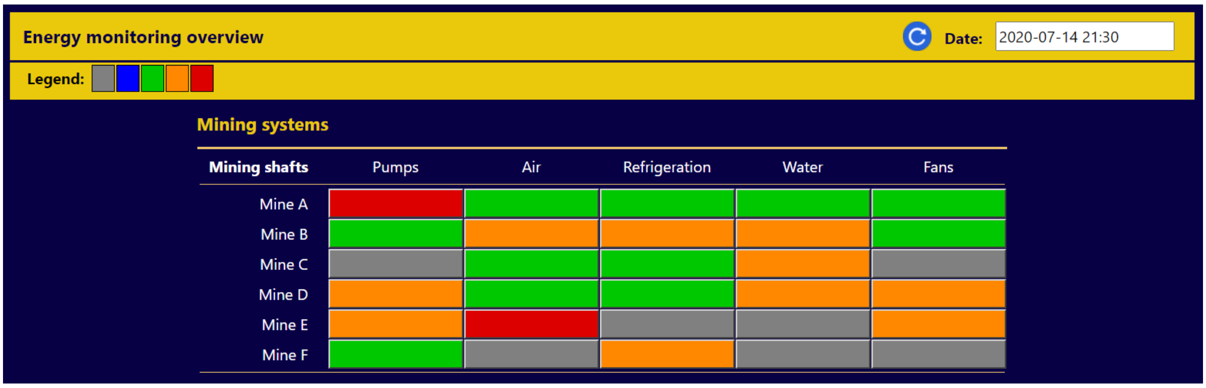

Figure 2.15: User interface block overview

Table 2.4: Legend for the user interface overview block

Key	Description	Colour
Good	The actual usage is below the target profile	
Bad	The actual usage is above the target profile	
Warning	The actual usage is below the target profile by 10%	
No data	There is no actual usage data	
Unknown status	The system is not setup	

2.6 System integration and verification

2.6.1 Integration and operation of the monitoring system

The three main parts of the proposed system are integrated to provide a complete energy monitoring solution. Figure 2.16 illustrates the entire system integrated as a process flow diagram showing the different paths taken from the mine database to the ESCo web-based system.

For the daily operation, the data extraction is performed according to the calculated intervals (Equation 2.1) for the actual power consumption. The data extracted is then transmitted via email (SMTP) to the ESCo database. The SMS notification system is implemented on the remote site to overcome the latency introduced from transmitting the data via email. This ensures that the notifications are sent out as the energy-wastage event is happening. The data transmitted via email is then processed and displayed on the web-based user interface.

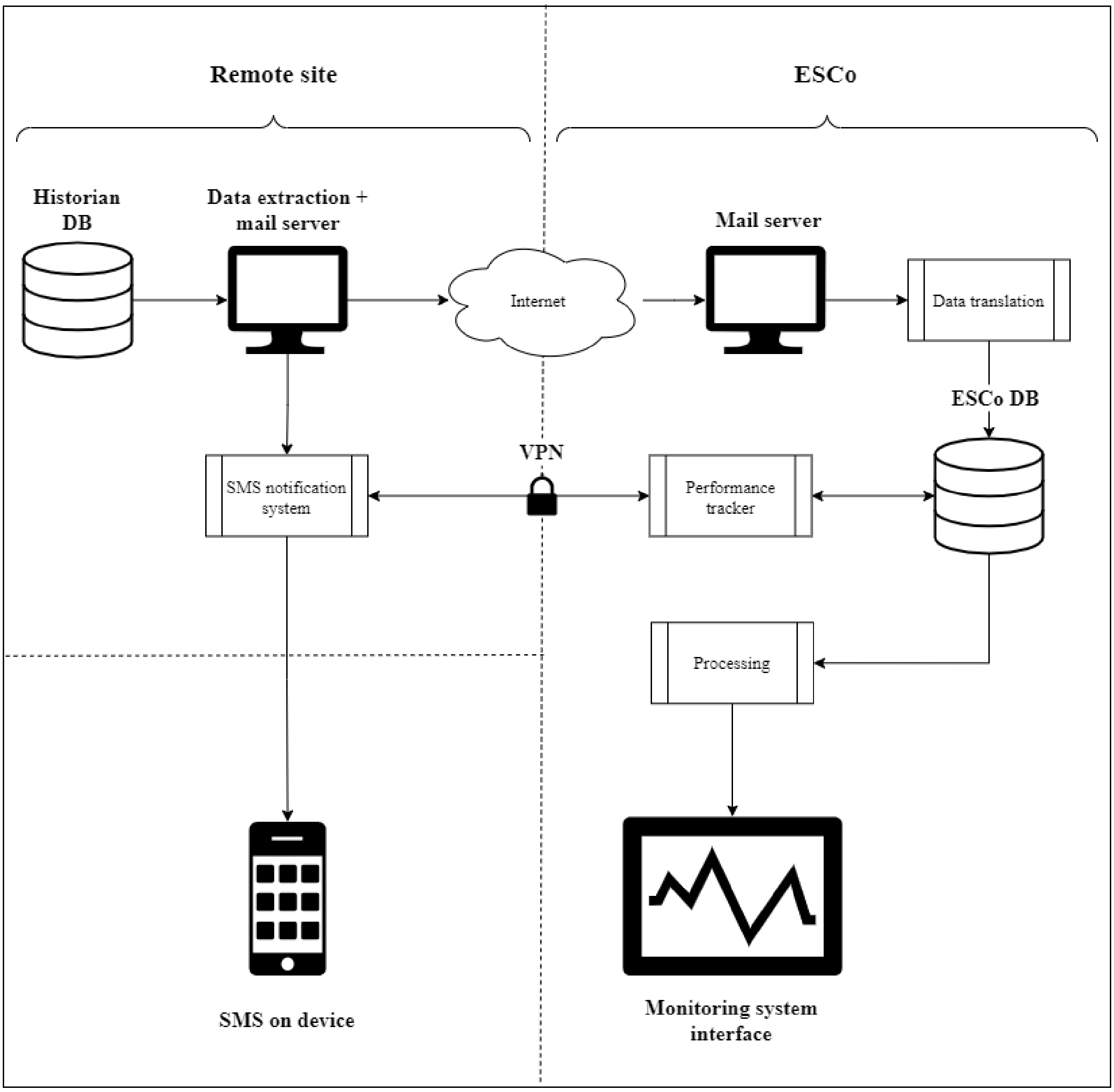

Figure 2.16: Monitoring system full integration

The performance tracker is used for continuous improvement. The target profiles are calculated according to the adjustments which may occur. Once the target profiles are feasible, they are updated for use in the daily operation. These target profiles are stored in the ESCo database, which means that updates made to them are immediately available for use in the daily operation.

2.6.2 Verification of the monitoring system

In order to verify the monitoring system, the requirements listed in Section 2.2 are evaluated against the implemented design. Table 2.5 is a recapitulation of the original system requirements of Table 2.2, with the inclusion of the sections in-text where the requirement was fulfilled. As shown on Table 2.5, all the design requirements and specifications were met, and the sections listed include screenshots and snippets of the system in operation.

Table 2.5: Monitoring system verification summary

Specification	Description	Design	Met
1. Performance tracker			
Baseline/Target creation	Targets and baselines should be created using custom data samples. Calculations on the samples given adjustments should be possible.	Section 2.4, Figures 2.5, 2.6	✓
Model re-evaluation	Implemented baselines and targets should be flexible enough to be re-evaluated and calculated depending on external changes.	Section 2.4	✓
2. SMS notification system			
Notify users	Linked users should be notified on energy-wastage events on their mobile devices.	Section 2.5.1, Figure 2.8	✓
Avoid overloading users	Notifications sent should not overwhelm the recipients.	Section 2.5.1	✓
Post-analytical auditing	A history of all the notifications sent out should be available for post-analytical auditing to quantify the notification trigger frequency.	Section 2.5.1, Figure 2.9	✓
3. User interface			
Display data	The power usage data of the main mining systems should be displayed in a simplified manner.	Section 2.5.2 Figures 2.12, 2.13,2.14,2.15	✓
Impact measurement	Additional metrics should be used to quantify the energy data into more simplified quantities.	Section 2.5.2 Figure 2.13	✓

The following section details a methodology which will be applied in order to validate the monitoring system.

2.7 System validation methodology

Figure 2.17 illustrates the methodology which will be used to validate the effectiveness of the monitoring system. The monitoring system will be implemented on existing energy saving projects on a South African gold mining group. To prove that the system works, it should mitigate energy wastage in a timely manner. This mitigation should be quantifiable in terms of energy and cost.

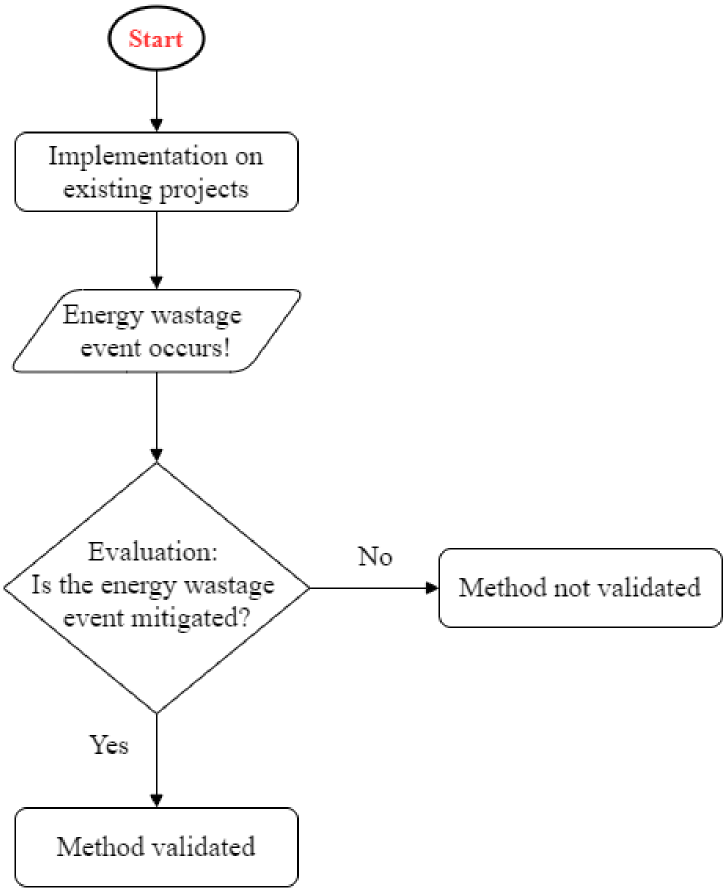

Figure 2.17: Monitoring system validation methodology

2.8 Conclusion

Section 2.2 summarised the requirements and design specifications of the monitoring system. The specifications were grouped according to the three functional parts of the system, namely the performance tracker, the SMS notification, and the user interface.

Section 2.3 discussed the method used to extract and transmit the energy data. The data extracted was used to model the targets as well as for the daily operation. This section also discussed techniques to adequately prepare the data in order to maintain accuracy. The performance tracker was developed in Section 2.4 to create and model baselines and targets using the extracted data samples and adjustments. These targets were implemented in Section 2.5 as the SMS notification system and user interface.

The steps taken to design the SMS notification system were discussed in Section 2.5.1. This section included a snippet of the SMS notifications as well as the method implemented to enable post-analytical auditing. Section 2.5.2 discussed the design of the user interface with examples of how the raw data will be visualised to address the problems identified in literature.

The full integration of the three functional parts of the monitoring system was discussed in Section 2.6.1. It detailed the daily operation of the system as well as the re-evaluation of the targets. Section 2.6.2 discussed the verification of the system and the methodology for its validation was discussed in Section 2.7.

Chapter 3

Results and validation

3.1 Preamble

In 2019, an ESCo implemented energy saving projects on a gold mining group which comprises of five mining shafts. These projects ranged from compressor control to ToU improvement. Four of the projects which involved four mining shafts were selected as case studies.

In Case study A, B, and C, past incidents which led to energy wastage were evaluated to show the efficiency of the monitoring system. Case study A also evaluated the overall performance of the project and quantified whether the intervention due to the monitoring system resulted in reduced deterioration over time. Case Study D evaluated the overall efficiency of the monitoring system and addresses the user engagement objective as well as the importance of accurate targets. Due to confidentiality agreements, the mines will be referred to as Mine A to Mine D.

3.2 Setting up the monitoring system

The monitoring system was implemented in phases on each of the mines. Common project types such as load shift and peak clipping were set up first on the user interface, and more specialised projects were included to the time-conscious SMS notifications. This section summarises the steps taken to setup the monitoring system for each of the mine's projects. This is the same process flow discussed in Chapter 2.

3.2.1 The acquisition of data

Table 3.1 summarises the different parameters selected for acquiring the energy data for the daily operation. The selection of these parameters was performed using the methods discussed in Section 2.3 and in Equations 2.1 and 2.2.

To calculate the extraction interval I_E (Equation 2.1), the following inputs where used:

- T_{Log} was measured manually to be approximately 120 seconds. The maximum and minimum recorded values were 146 seconds (+23%) and 101 seconds (-16%) respectively.
- PLC_{Log} is instantaneous and can be approximated to 1 second.
- The time delay is selected as 25% of T_{Log} which is 30 seconds. This was selected based on the maximum recorded T_{Log} value of 146 seconds (+23%) and rounded up.

The ideal extraction interval is, therefore, calculated as:

$$I_E = 120 + 1 + 30 = 151 \ \ seconds$$

The lowest data Interval I_D (Equation 2.2) is, therefore:

$$I_D = 2 \times 151 = 302 \ \ seconds$$

Table 3.1: Selected parameters for the data transmission

Parameter	**Selection**
Transmission mode	Simple Mail Transfer Protocol (SMTP)
Data extraction interval	2.5 minutes
Data interval	5 minutes
Data transmission interval	2 minutes

3.2.2 Performance tracker setup

The sample data used for the initial baselines and targets were the previous year's performance. This means that the performance of each calendar year will be measured against a baseline of the year preceding it. This sample was chosen on the basis that the projects would have been implemented and the operation was feasible to run through a second-year cycle.

Table 3.2 summarises the selected parameters for the performance tracker. The Baseline Model was developed by averaging the power profiles of the chosen sample data. Three operational modes were calculated and stored to correspond to "Weekdays", "Saturdays" and "Sundays". The developed baselines were compared to their corresponding present project performance to note discrepancies. Discrepancies such as unattainable performance goals prompted a recalculation of the model.

The Target Model was then developed by using the Baseline Model as a starting point. The adjustments implemented into the targets were project specific. These ranged from energy reduction for specific time frames during the day to reducing the overall consumption for the entire profile.

Table 3.2: Selected parameters for the performance tracker

Parameter	**Selection**
Baseline Model	Constant
Target Model	Energy-neutral
Initial data sample	Previous year per-month average

The effectiveness of the baselines and targets is demonstrated in the following sections through case studies and is measured by their ability to mitigate energy wastage.

3.2.3 Performance tracker implementation

The user interface was implemented for the projects which involved the main mining systems. Projects with a high risk of energy wastage were added to the SMS notifications first to aid in tracking the unwanted events. These high risk projects were identified as projects which relied on human control to either switch off or cut back machinery through the different tariff times throughout the day.

A total of nine projects were added to the SMS notification system by January 2020. These included individual level projects for compressed air systems, pumping and refrigeration.

3.3 Case study A: Compressed air system

Addresses Point 3 of the technical objectives in Section 1.3.

3.3.1 Background

An ESCo implemented a compressor project which involved integrating the two compressed air networks of Mine A and Mine B. Figure 3.1 is a schematic layout of this particular case study. The project began when pipe leaks at Mine B were repaired and it was then possible for the compressors to be throttled[9]; however, the compressors were throttled to a point where they began to blow-off[10], leading to air wastage. The compressor at Mine A was operated on a low guide vane angle and was on the verge of blow-off. Integrating these two networks would ensure that none of the compressors blow-off, and that there was potential for energy savings.

As illustrated on Figure 3.1, Mine A is a hydro-power shaft mine with one compressor supplying five production levels, and Mine B has a compressor ring which contains four compressors supplying nine production levels. The two compressed air networks are linked with a valve underground on 22 Level. The compressor specifications are shown on Table 3.3.

Table 3.3: Mine A and Mine B compressor specifications

Compressor	**Size**
Mine A Compressor 1	4 200 kW
Mine B Compressor 1	4 200 kW
Mine B Compressor 2	4 200 kW
Mine B Compressor 3	3 200 kW
Mine B Compressor 4	4 200 kW

The project involved switching off the compressor at Mine A and supplying its production levels with Mine B's compressor ring. This would stop the need to throttle the compressors at Mine B, thus avoiding blow-off. Incidents occurred where the compressor at Mine A was switched on, leading to the cancellation of the energy savings acquired through the integration.

The following sections illustrate the severity of the incidents before and after the implementation of the monitoring system.

[9] Compressor throttling: reducing the compressor guide vane angle in order to reduce its output power
[10] Compressor blow-off: releasing the compressor pressure in the event of excess pressure build up

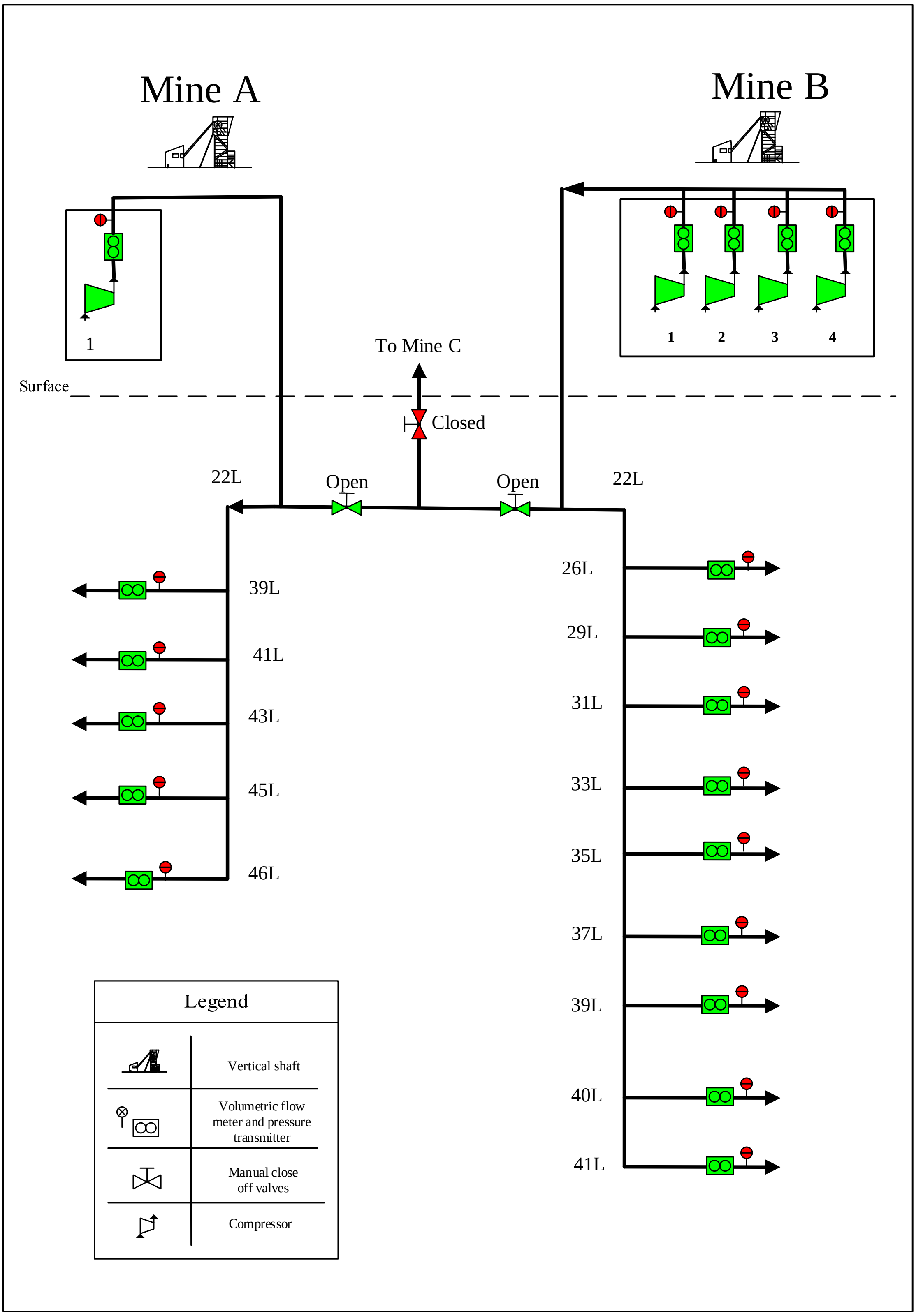

Figure 3.1: Compressed air reticulation for Mine A and Mine B

3.3.2 Incident: Before implementation

Incident on the 19th of January 2020

Figure 3.2 illustrates an incident which occurred on the 19th of January 2020. The compressor at Mine A was switched on at 12:00 and ran throughout the night. It was only switched off on the 20th of January at 15:00. The 27 hours for which the compressor ran out of the project scope owing to negligence totalled 51 MWh, which has an energy cost of R36 853.

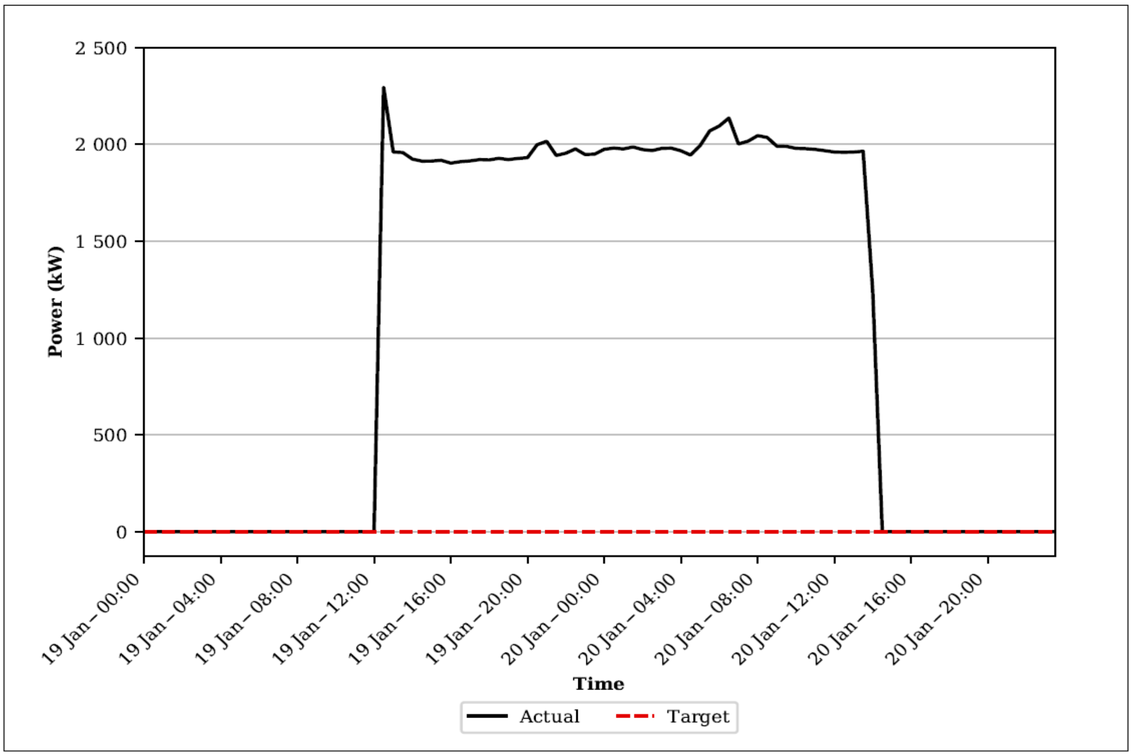

Figure 3.2: Mine A's compressor power profile for 19 Jan to 20 Jan 2020

This incident went unnoticed because there was no system in place to mitigate the energy wastage as it occurred. If the wastage had been noted earlier, this would have been avoided. Owing to this incident, compressor power targets were then calculated for both Mine A and Mine B, and the project was added to the monitoring system on the 25th of January 2020.

The target for the compressor at Mine A was set to 0 MW, indicating that the notifications would be triggered if it was switched on. The targets for Mine B's compressor ring were set up to only allow two compressors to operate throttled so as to keep the power under 8.5 MW during the day and 7 MW during evening peak times. This was done to prevent future energy wastage.

3.3.3 Incidents: After implementation

The project faced challenges which led to the integration being temporarily reverted. Four notable time periods where the project was halted are listed on Table 3.4. During these periods, the monitoring system targets for both Mine A and Mine B were readjusted to include the interruptions to ensure that the notifications did not trigger unnecessarily.

Table 3.4: Date periods where the integration project was halted

Time period	**Reason for reverting**
3 March – 25 March 2020	Mine B underwent scheduled maintenance on the four compressors; supply to Mine A was, therefore, not possible.
13 May – 30 May 2020	There were complaints from the miners on Mine B about inadequate pressure on the lower levels. This made it difficult for it to supply Mine A.
29 Aug – 30 Aug 2020	Scheduled maintenance on the Mine B compressor ring.
28 Sep – 7 Oct 2020	There was a fall-of-ground on the supply line between Mine A and Mine B which caused significant damage to the compressed air pipes. Mine A had to supply its own levels.
13 Nov – 16 Nov 2020	Mine B underwent scheduled maintenance on the four compressors; supply to Mine A was, therefore, not possible.

Incident on the 27th of March 2020

On the 27th of March, an incident similar to the one illustrated on Figure 3.2 occurred, where the control operator unknowingly switched on the compressor at Mine A. Figure 3.3 illustrates the power profile of Mine A's compressor for this specific date. Owing to the monitoring system, the ESCo engineer was immediately notified and managed to communicate with the operator to switch off the compressor.

An incident like this which fell close to a weekend would previously have lasted well over 20 hours; however, as illustrated on Figure 3.3, it was resolved in just under two hours. The loss was limited to approximately R3 407 instead of R36 000.

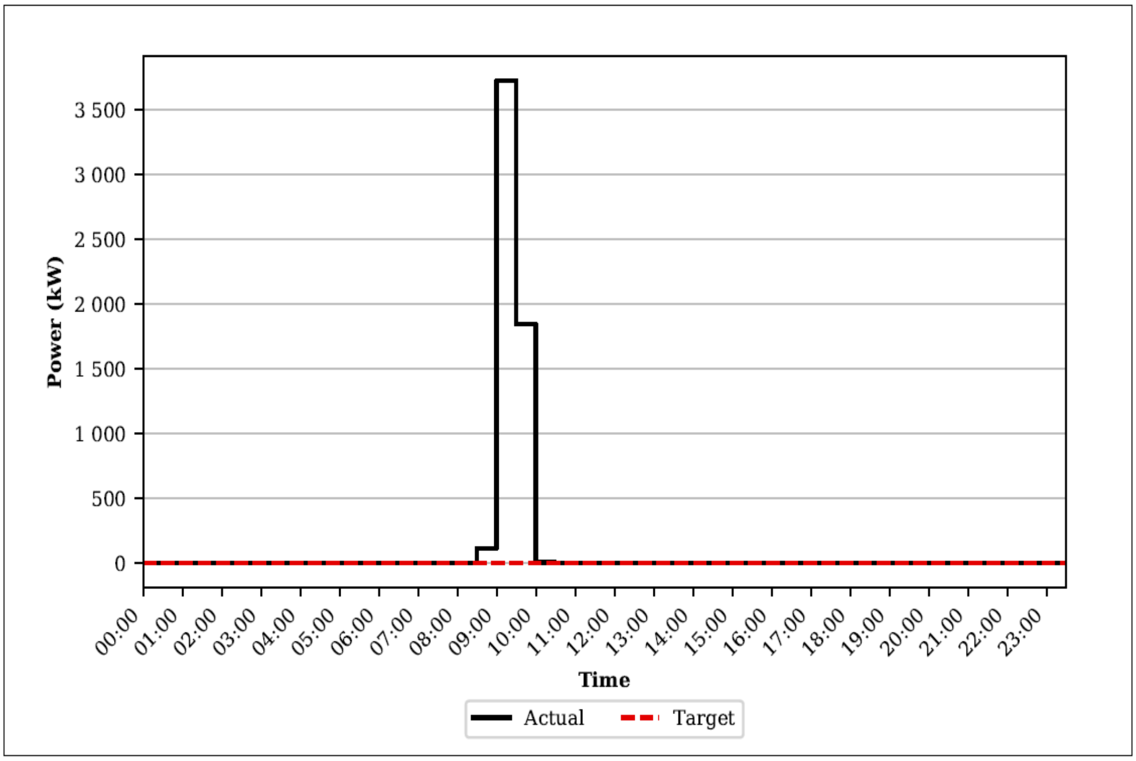

Figure 3.3: Mine A's compressor power profile for 27 March 2020

Incident on the 28th of August 2020

Maintenance on Mine B's compressor ring was scheduled to be performed between the 29th and the 30th of August. This meant that the compressor at Mine A would only be switched on during the approved maintenance dates to supply its production levels; however, as illustrated on Figure 3.4, an incident occurred. The compressor at Mine A was switched on prematurely on the 28th of August at 07:00, 17 hours before the approved maintenance period. Owing to the monitoring system, the ESCo engineer promptly followed up with the control operator to find out if this change in the approved schedule was warranted. The misunderstanding was immediately rectified, and the compressor was switched off.

Had this event gone unnoticed, the compressor would have remained operational for 17 hours at 2 000 kW, costing the project approximately R60 000. This energy-wastage event was immediately averted, and the negative cost impact was limited to approximately R5 285. The potential negative cost impact was calculated using the high-demand tariffs of Table 1.2.

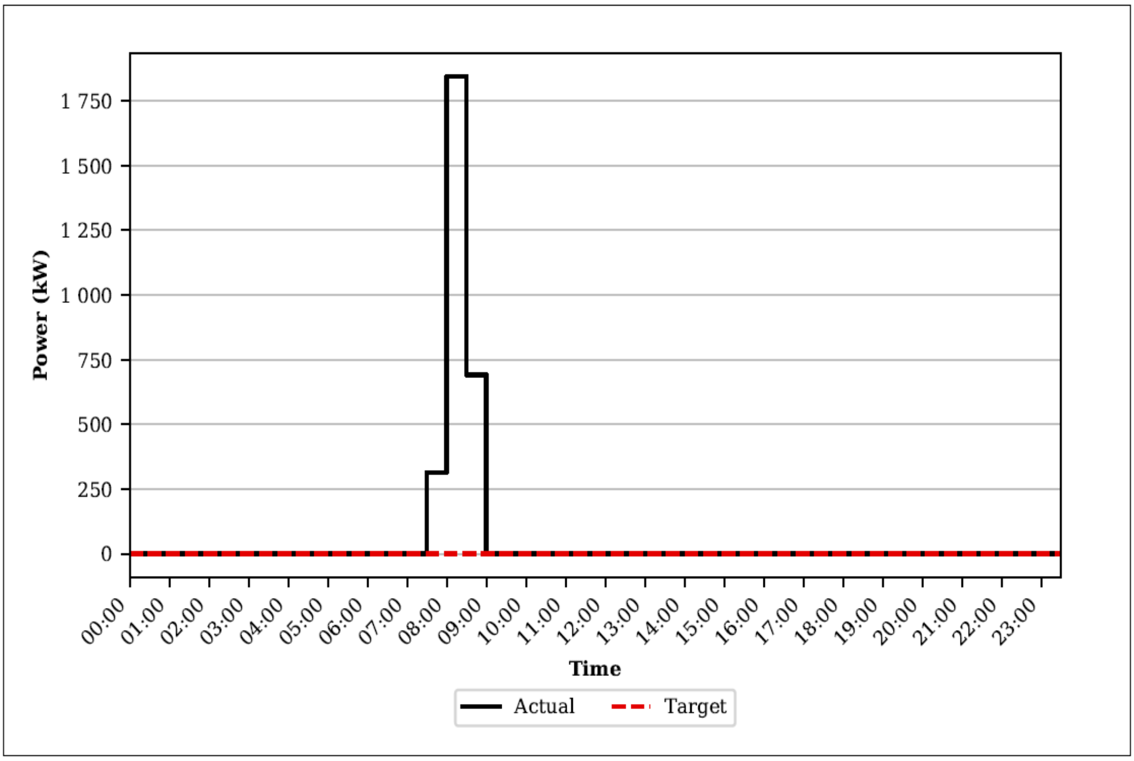

Figure 3.4: Mine A's compressor power profile for 28 August 2020

3.3.4 Evaluating project performance

Section 1.1.4 discussed how projects begin to deteriorate three months after they are implemented due to reasons such as negligence and improper maintenance. Figure 3.5 illustrates the performance of the compressed air network integration project with respect to the impact savings experienced on Mine A. Since the target power for the Mine A compressor is 0 MW, the impact savings can be calculated using Equation 3.1:

$$Impact_{Saving} = AVG_{Usage} \; - \; ACT_{Usage} \tag{3.1}$$

Where:

AVG_{Usage} = the average monthly energy usage before project implementation
ACT_{Usage} = the actual monthly energy usage

As illustrated on Figure 3.5, the project performed well for the first three months but under performed in March, May, October and November of 2020; however, this was due to the reasons listed on Table 3.4. The ESCo engineers, with the aid of the monitoring system, continuously followed up on the project interruptions to ensure that the performance would not deteriorate. The momentum of the project was maintained due to constant intervention, and after twelve months, in November 2020, the impact savings had not drastically reduced.

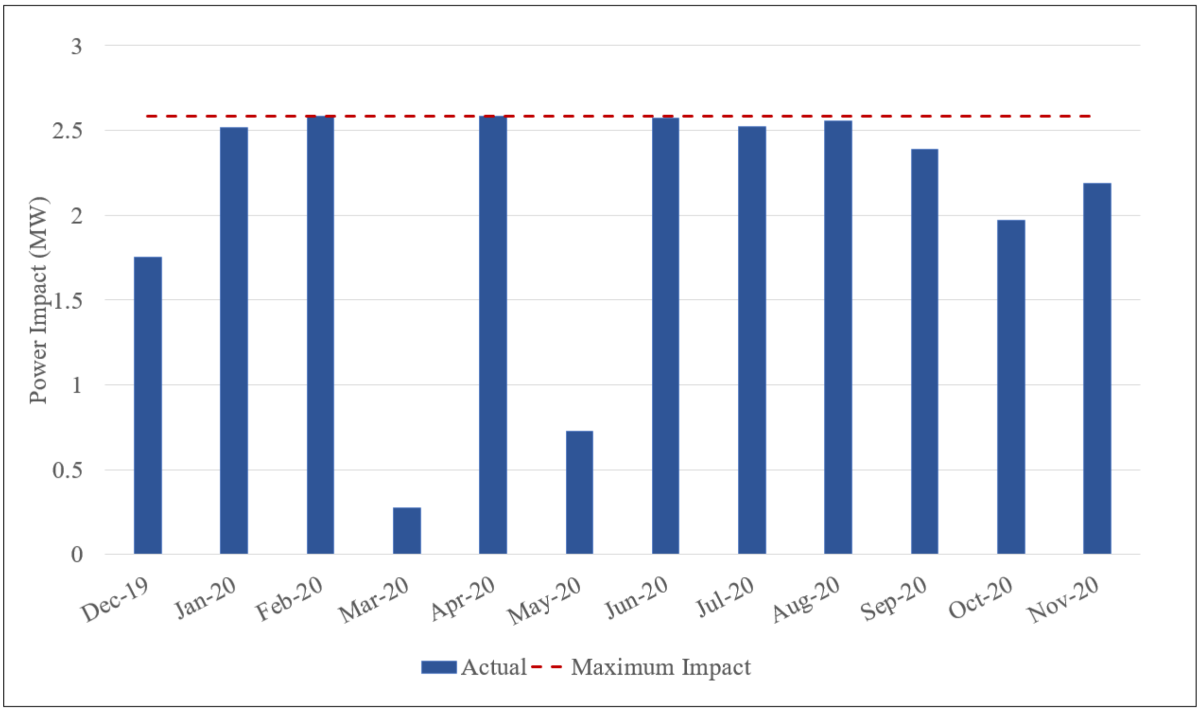

Figure 3.5: Mine A's compressor power impact savings

Since the interruptions shown on Table 3.4 were not due to negligence, Figure 3.5 can thus be adjusted to show the overall performance due to the control operators. This is illustrated on Figure 3.6. As illustrated, the performance of the project was constant over the twelve months, with the only problems being due to the incidents caused by the control operators.

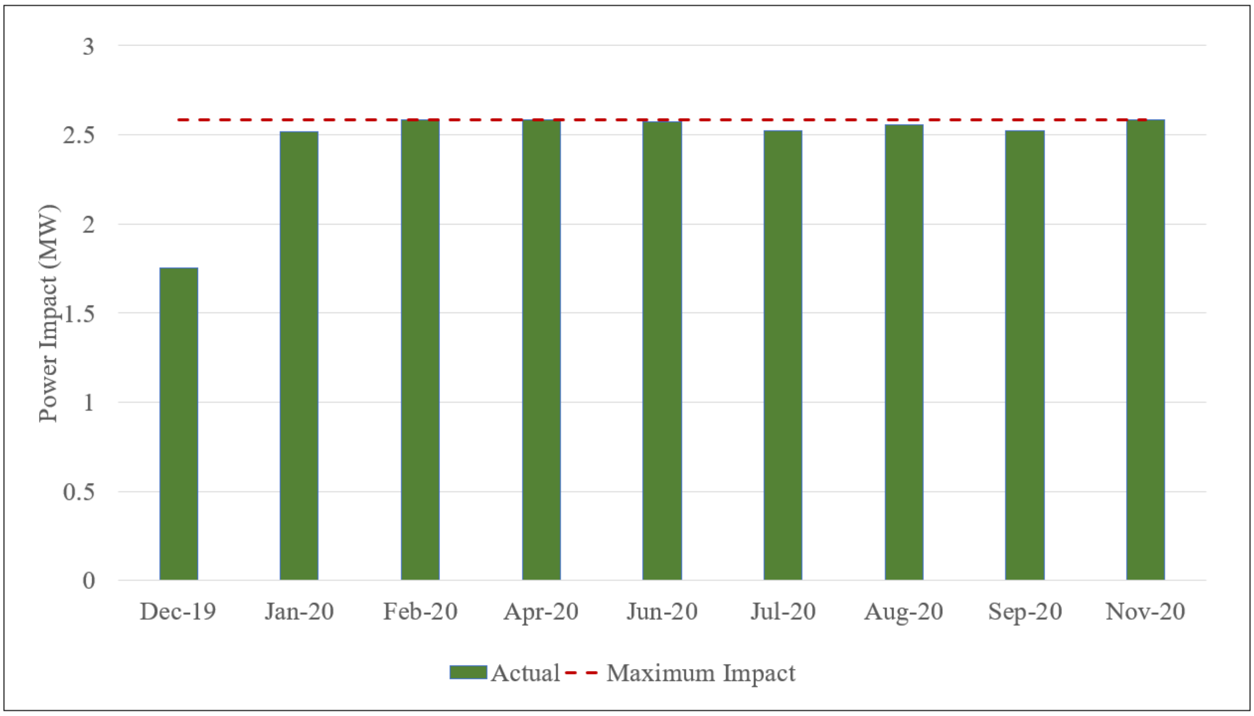

Figure 3.6: Mine A's adjusted compressor power impact savings

Owing to the monitoring system, there was constant communication between the ESCo engineers and the control operators, which ensured that energy wastage incidents did not occur due to negligence, and thus improved the long-term performance of the integration project.

3.3.5 Summary

The proposed monitoring system was successful in mitigating energy wastage in the compressed air network integration project on two notable incidents. These incidents involved the negligent use of the Mine A compressor outside of the project scope. On the 27th of March, the negative cost impact was limited to approximately R3 407, and such an incident would previously have cost the project approximately R36 000. On the 28th of August, the negative cost impact was limited to approximately R5 285 averting a potential loss of R60 000 due to operating the compressor outside of the approved maintenance dates.

The combination of the SMS notifications as well as the user interface made it possible for the ESCo engineer to realise when a wastage event was in progress, thus stopping it and securing the project savings. Due to this constant intervention, especially during the time periods where the project was halted, the overall performance was maintained, and the project did not deteriorate due to negligence.

3.4 Case Study B: Water reticulation system

Addresses Point 3 of the technical objectives in Section 1.3.

3.4.1 Background

Water reticulation projects, which involve optimising pumping schedules, were implemented on Mine D. By moving the pumping to outside of peak times, energy cost savings were acquired through the ToU tariffs. Figure 3.7 illustrates the schematic layout of Mine D's water reticulation system. Water is sent down from surface to all the production levels until it reaches the lowest level (labelled as the Flooding Level on Figure 3.7). The water is then pumped out from this level and out to Mine C.[11]

Mine D contains three pumping stations. Two of the stations house the smaller transfer pumps which move water from the Flooding Level to the holding dams. The main dewatering pumps are then used to pump water out of the mine. The load shift project was implemented on the main dewatering pump station because it contained holding dams which enable load shift to be performed.

Incidents occurred where the control operators switched on the pumps before the peak time ended, leading to excessive energy costs. Incidents where the dams were full were excluded in this case study because flooding the dams would cause safety concerns.

[11] The peak times are from 07:00 to 10:00 and 18:00 to 20:00 for the low-demand season, and from 06:00 to 09:00 and 17:00 to 19:00 for the high-demand season.

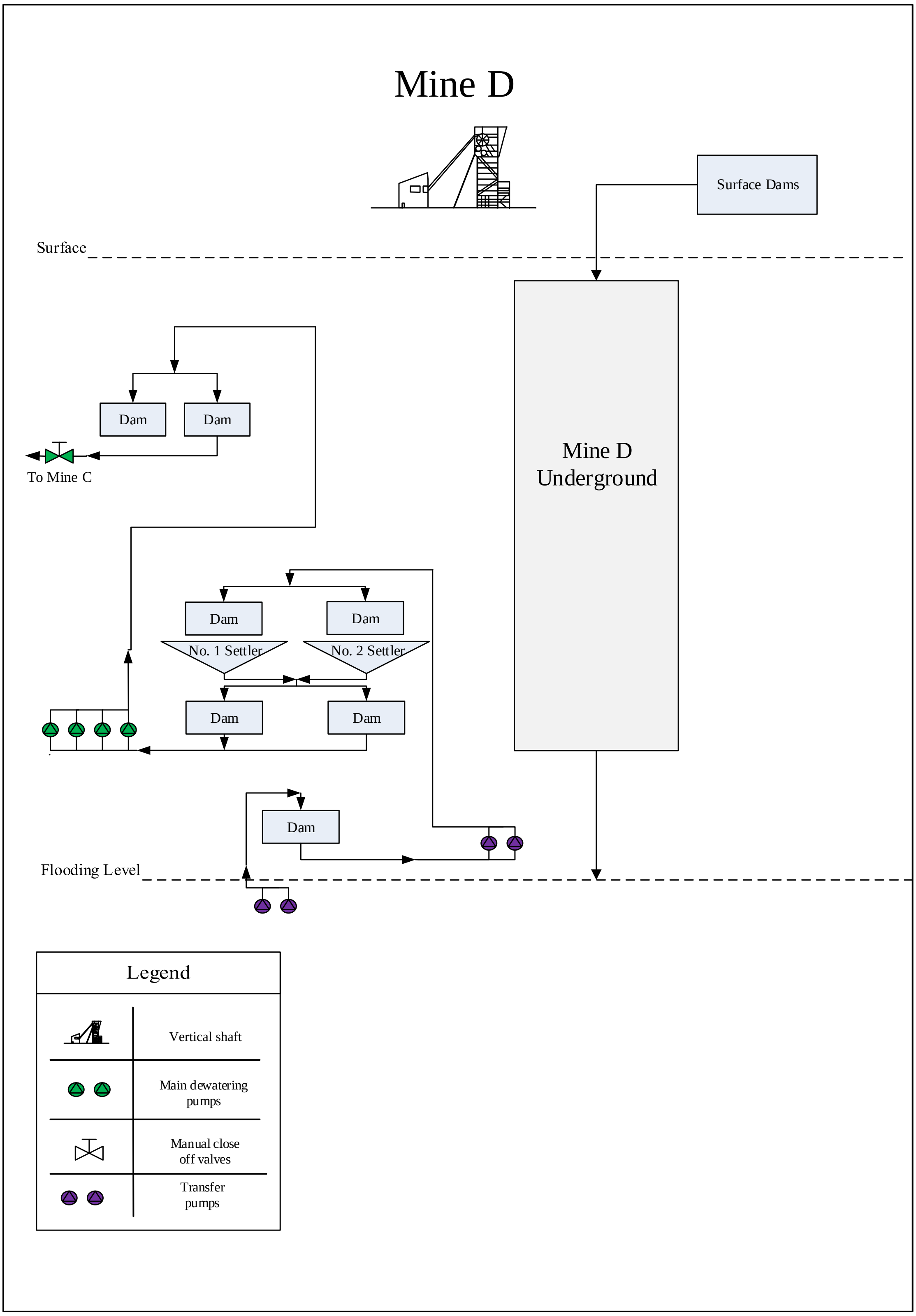

Figure 3.7: Water reticulation for Mine D

3.4.2 Incidents: Before implementation

The project faced difficulties from February until May 2020. The dams were constantly overflowing and load shifting was, therefore, not performed. In the month of April, water was not sent down Mine D, and thus there was no need to pump water out. These months were, therefore, excluded from the Case study. From June 2020, the pumping project was in full effect.

Table 3.5 shows the energy-wastage incidents which occurred in Mine D between the 5th of June and 10th of July 2020. These incidents exclude instances where the dams were full and load shifting could not be performed.[12]

Table 3.5: Mine D's incidents before the monitoring system was implemented

Date	**Start**	**End**	**Missed opportunity**	**Energy**	**Cost**
05 Jun	05:00	08:40	20 minutes	391 kWh	R1 450
23 Jun	17:00	18:30	30 minutes	501 kWh	R1 858
02 Jul	06:00	08:30	30 minutes	555 kWh	R2 059
03 Jul	05:00	08:30	30 minutes	874 kWh	R3 242
09 Jul	06:00	08:10	50 minutes	1 322 kWh	R4 904
10 Jul	06:00	08:30	30 minutes	677 kWh	R2 511

The most prevalent problem with pumping load shift projects is the premature switching on of the pumps during peak times. As shown on Table 3.5, missed opportunities often occur during the last 30 minutes of the peak period. Taking the 3rd of July from Table 3.5 as an example, if the missed opportunity energy had been outside the peak time, it would have landed on the standard time. The standard time energy cost is 67% less than the peak time energy cost; therefore, the energy would have cost R1 070.

The six incidents which occurred had a combined negative cost of over R16 000. Targets were implemented for this project, and active monitoring was enabled on the 15th of July 2020.

[12] Tariff used: 2019-2020 Eskom Megaflex cost $\leq$300 km $\geq$500 V & <66 kV + admin. High-demand season peak times: 06:00–09:00 and 17:00–19:00.

3.4.3 Incident: After implementation

Incident on the 31st of July 2020

On the 31st of July, an incident occurred where the operator prematurely switched on the pumps with 50 minutes of peak time remaining. Owing to the monitoring system SMS notification and user interface, however, this only lasted for 25 minutes as illustrated on Figure 3.8. The ESCo engineer in charge of monitoring Mine D's pumping project notified the control operator at the mine and averted 30 minutes of energy wastage. This saved the project approximately R2 782.

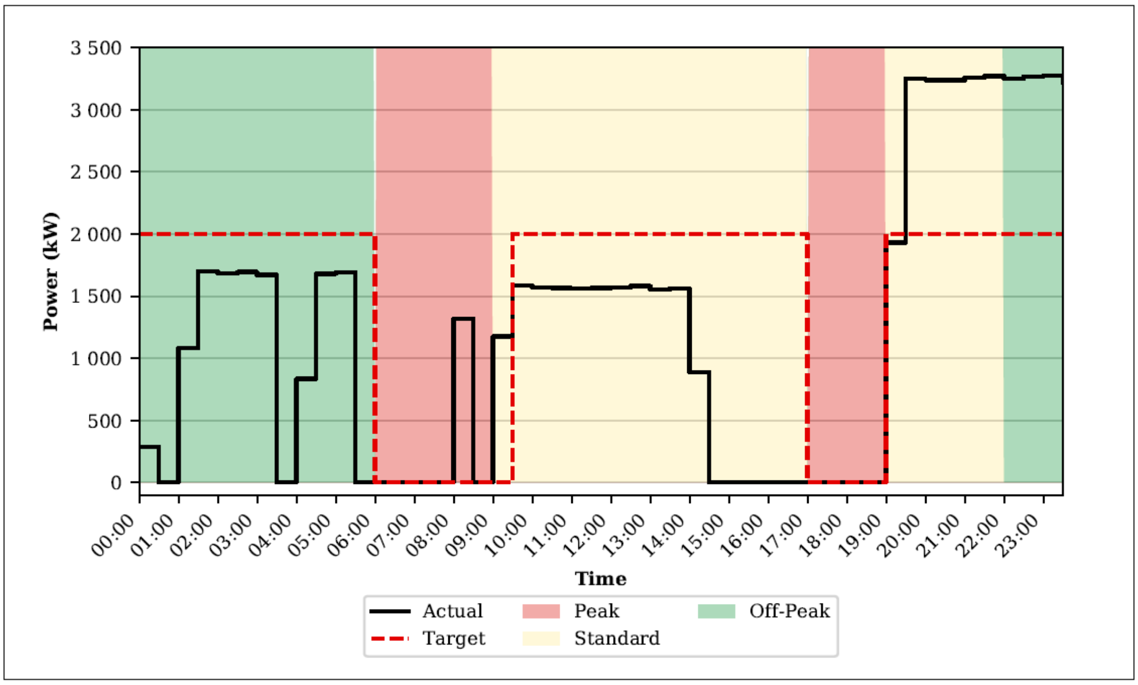

Figure 3.8: Mine D's pumping power profile for 31 July 2020

Incident on the 11th of August 2020

On the 11th of August, a similar incident occurred where the pumps were switched on during peak time with almost 100 minutes remaining. Due to the prompt response of the ESCo engineer with the aid monitoring system, this was limited to 20 minutes as shown on Figure 3.9. This averted a potential loss of approximately R2 590.

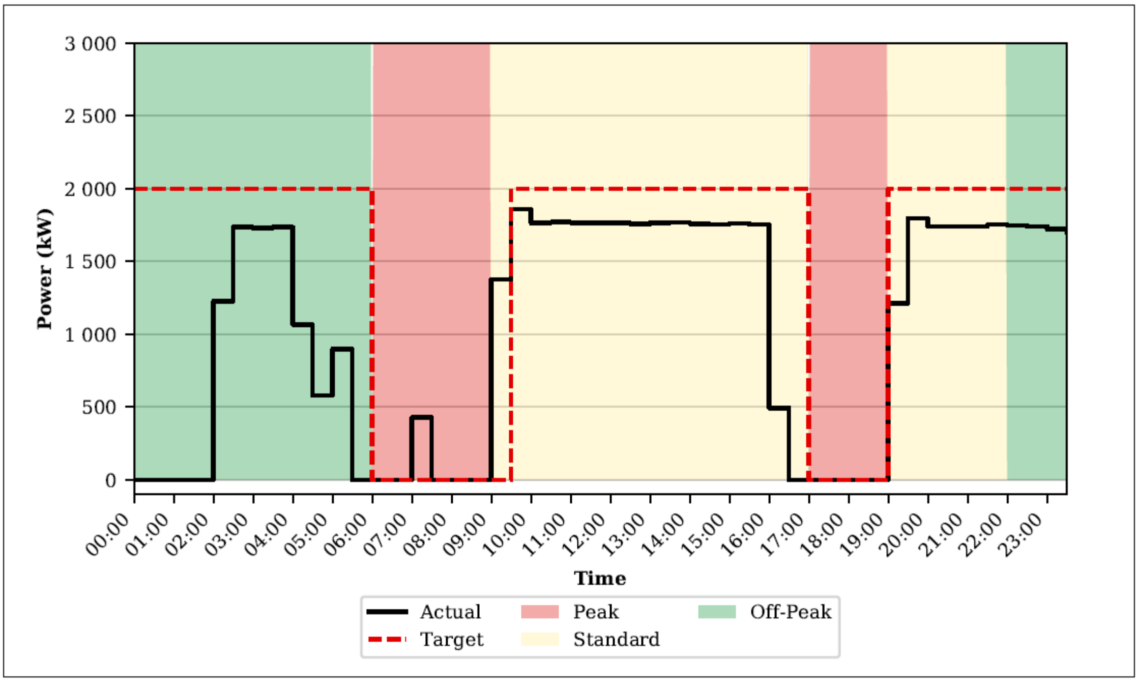

Figure 3.9: Mine D's pumping power profile for 11 August 2020

3.4.4 Summary

The monitoring system was successful in mitigating energy wastage in load shifting projects on Mine D. This proved that the system was highly efficient in mitigating energy wastage in time-conscious projects, as it saved the project approximately R5 372 on two notable incidents. Prior to the implementation of the monitoring system, Mine D experienced missed opportunities to the value of R16 000 between June and July due to operating the pumps in the more expensive peak periods.

If the same trend of five or more incidents occurring in a month had continued, in a year, this load shift project would have incurred a negative cost impact of up to R0.2-million due to energy wastage. Implementing the monitoring system on all the load shifting projects in the mining group has the potential of mitigating energy wastage to the value of R2-million annually. This is calculated using Mine D as a benchmark for the other four mining shafts on the basis that five incidents occur in a 30-day period.

A limitation was identified in the monitoring system where it flagged energy-wastage events when the dams were overflowing. The system only used the energy values and targets but did not include additional variables which could potentially influence the triggering frequency.

3.5 Case Study C: Hydro-power turbine generator

Addresses Point 3 of the technical objectives in Section 1.3.

3.5.1 Background

Mine D, illustrated on Figure 3.7 contains a hydro-power generator which uses the water sent down the shaft from surface. The electricity generated is then used to offset the energy usage within the shaft, leading to a cost saving on the monthly electricity bill. Incidents occurred where the turbine generator tripped, resulting in no electricity generation. Although this is not an implemented project, ensuring that the generator is always operational provided scope for relatively easy cost savings.

The generator has a rated output power of 2 MW and is scheduled to operate continuously during weekdays to capitalise on the water sent down for the mining shifts. On weekends, the schedule changes depending on the shift type (i.e., on a mining weekend, it is switched on, and it is switched off when there's no mining activity). For this case study, only weekdays were considered, as they are the only time periods where the generator should never be switched off. The following sections highlight the severity of incidents where the generator was not operational.

3.5.2 Incidents: Before implementation

Table 3.6 shows the incidents in 2020 where the generator tripped or was not switched back on from the weekend due to negligence. As a result of these negligent acts, there was missed opportunity in terms of electricity generation, and the potential in the free-falling water was wasted.

From Table 3.6, the following can be noted:

- On average, a minimum of two incidents occurred in a month, and they averaged six hours per incident.
- February had a total of 49 hours where the generator was not operating. This had the highest missed opportunity of 98 MWh.
- The average missed opportunity on months where incidents occurred was 32 MWh.

The month of April was excluded because no production took place in the shaft meaning that no water was sent down.

Table 3.6: Mine D's generator incidents before the monitoring system was implemented

Month	No. of Incidents	Total	Longest Duration	Missed Opportunity
Jan	3	12 hrs	6 hrs	24 MWh
Feb	3	49 hrs	39 hrs	98 MWh
Mar	3	11 hrs	7 hrs	22 MWh
May	3	18 hrs	8 hrs	36 MWh
Jun	0	0 hrs	0 hrs	0 MWh
Jul	0	0 hrs	0 hrs	0 MWh
Aug	2	8 hrs	5 hrs	16 MWh
Sep	4	13 hrs	5 hrs	26 MWh
Oct	1	3 hrs	3 hrs	6 MWh

These incidents occurred because there was no system in place to actively monitor when the generator was not operational during the mining time periods. This caused a wastage in energy as it would have been used to offset the overall shaft usage. The control operators and ESCo engineers only depended on the SCADA, which, according to literature, is not the best when it comes to active monitoring. On the 23rd of October 2020, active monitoring was implemented for the Mine D generator project.

3.5.3 Incident: After implementation

Table 3.7 shows dates when the generator was switched off during mining times due to other reasons and not negligence. For the purpose of this study, these dates are excluded.

Table 3.7: Dates when Mine D's turbine generator was switched off

Date	Reason
27 Oct 2020	Scheduled maintenance on the generator.
10 Nov 2020	Mine-wide power failure.

Incident on the of 3rd of November 2020

On the 3rd of November, an incident occurred where the generator's motor tripped. Figure 3.10 illustrates the power generation profile for this specific date. The Target (red dashed line) was set to 500 kW, meaning that if the power generated was lower than the target, the notification would trigger due to a potential trip. The Expected profile (green dashed line) is the ideal power output.

Figure 3.10: Generated power profile for the 3rd of November 2020

Owing to the monitoring system, the control room operators were immediately notified of the energy-wastage event by the ESCo engineers, and they restarted the generator. As illustrated on Figure 3.10, the energy wastage was limited to less than one hour, yet previously, such an event would go unnoticed for an average of six hours. A potential loss of generation of 12 MWh was only limited to approximately 1.5 MWh.

3.5.4 Summary

The proposed monitoring system was successful in mitigating energy wastage in the turbine generator project on a notable incident. On the 3rd of November, a potential loss of generation of 12 MWh was only limited to approximately 1.5 MWh. Owing to the monitoring system, this event was noticed and stopped in time. Since electricity was generated by the mine and not purchased from the national electricity supplier, Eskom, a cost saving can thus be calculated. Referencing the standard electricity tariffs for the low-demand season, shown on Table 1.1, the potential negative cost impact of R11 304 was limited to R1 413.

If the trend of the generator tripping was to continue for another year, the potential energy cost saving due to the intervention of the monitoring system could be R25 000 monthly or R0.4-million annually. These cost values are calculated using the trends on Table 3.6 and estimating a general electricity tariff per season from Tables 1.1 and 1.2.

3.6 Case Study D: Continuous target improvement

Addresses the user engagement objectives in Section 1.3.

3.6.1 Preamble

The targets need constant improvement in order to ensure the efficiency of the monitoring system. Targets which become unfeasible over time due to system changes need to be readjusted and tested to maintain the effectiveness of the monitoring system. During the implementation of certain projects, the targets became unfeasible and, therefore, needed to be recalculated. Using the logs generated from the SMS notification system, post-analytical data was obtained to evaluate which of the notifications triggered the most. The logs also provided information on targets which triggered unnecessarily due to machine start-up power spikes (inrush current).

3.6.2 Control valve monitoring

Mine C implemented a compressor control valve project with the aim of reducing the individual level flows in order to throttle the compressors. This involved creating baselines and targets of the different level flows and matching them with the pressure set points. Since most of the valves are operated manually, constant monitoring was required.

In April 2020, the target flows for levels 33, 35, and 36 were adjusted in order to throttle the compressors even more; however, as illustrated on Figure 3.11, the new targets resulted in the notifications triggering too frequently. This resulted in a reduction of the usefulness of the notifications to the extent of them being perceived as insignificant. This prompted a readjustment of the targets using the performance tracker.

In July and August 2020, the targets were recalculated by selecting a different sample period and reducing the profile adjustments. Owing to this adjustment, a steady decline of triggered notifications was experienced as shown on Figure 3.11. The number of triggered notifications in a month for Level 36 reduced from a maximum of 30 in July to just over two in August and September. This ensured that each notification triggered was of high importance, thereby ensuring efficient monitoring and user engagement.

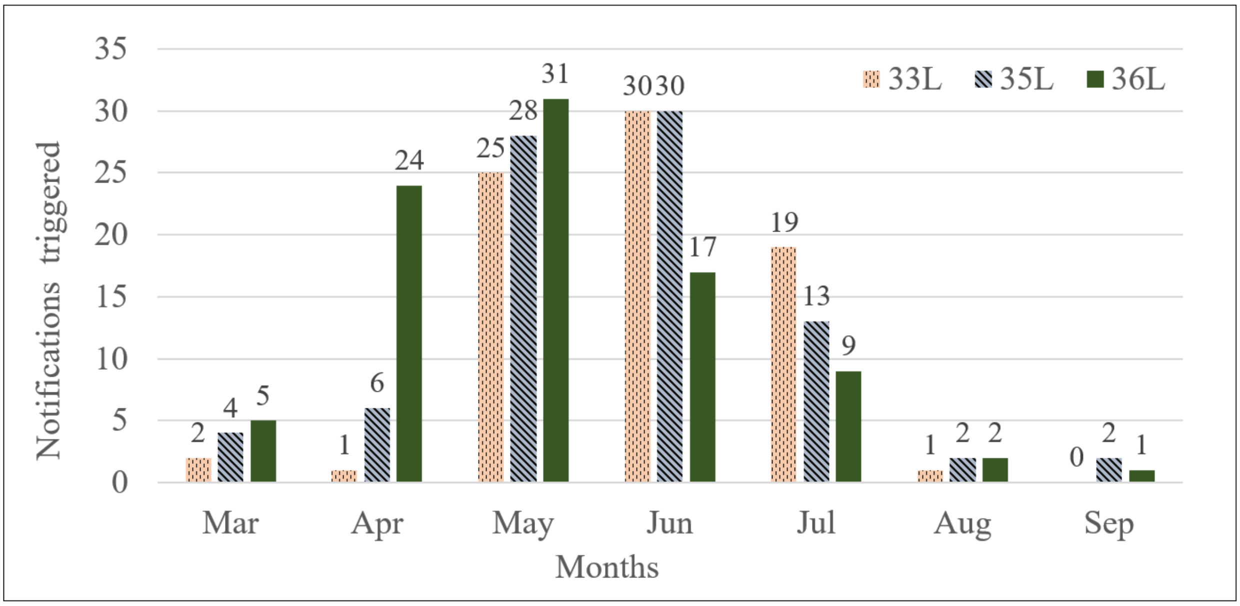

Figure 3.11: Mine C's valve control notification triggers

3.6.3 Compressor power monitoring

Targets for Mine B's compressors were recalculated as soon as the integration project mentioned Case Study A was in full effect. As illustrated on Figure 3.12, in the month of July, the targets set up had problems which lead to the notifications triggering 16 times during the month. This was mainly caused by both the targets not being feasible as well as the system not being designed for the high start-up power of the compressors. The power spikes would give a usage value just above the target for a short time period, giving the illusion of energy wastage.

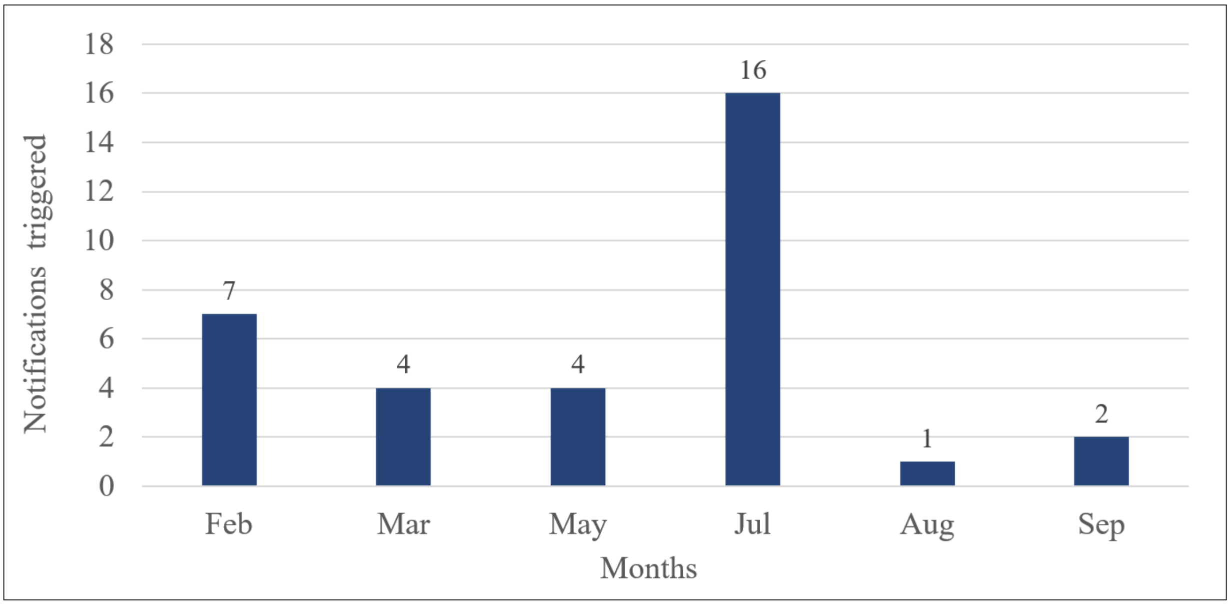

Figure 3.12: Mine B's compressor power notification triggers

From August onwards, the targets were then recalculated to allow for a more feasible usage value in order to avoid constant triggering. Allowance for the power spikes was also incorporated into the new targets, and, as illustrated on Figure 3.12, there was a reduction in the triggered notifications to just two in September. This ensured that each notification triggered was of high importance, thereby ensuring efficient monitoring.

3.6.4 Summary

Figures 3.11 and 3.12 illustrate how the monitoring system, and more specifically the performance tracker and SMS notification logs, continuously ensured user engagement. Identifying and rectifying frequent triggers as highlighted in Section 1.2.1.

This ensured that each energy-wastage incident was of high importance and reduced the perception of insignificance; however, had the SMS notification logs been audited earlier, the possibility of the notifications being perceived as insignificant would have been addressed at an earlier stage.

3.7 Summary of results

The monitoring system was implemented on five mining shafts to service different project types. Four projects were used as case studies to validate the effectiveness of the monitoring system.

Case Study A and Case Study B showed positive results in stopping energy-wastage events and became the foundation in the implementation of the monitoring system on additional projects. The impact saved was discussed as well as the potential impact on additional projects on other mining shafts, especially in the load shifting projects. Limitations were also discussed in the case studies, and these will form the future recommendations. Case Study A also evaluated the effectiveness of the monitoring system when it came to the maintenance of the overall performance of the project over twelve months.

Case Study C showed how the monitoring system was able to stop energy wastage in a turbine generator project. It also showed how versatile the monitoring system was with its ability to monitor maximum as well as minimum energy values. The incidents before and after the implementation of the monitoring system were then discussed.

Case Study D exhibited how the post-analytical auditing of the SMS notification logs promoted user engagement through the identification of frequently triggered notifications. This ensured that each notification triggered was perceived with high importance. The limitations of the case study were also discussed.

Table 3.8 summarises the validation of the monitoring system through the case studies.

Table 3.8: Monitoring system validation summary

Objective	**Validated by**	**Why it is validated**
Technical objective: Point 1.	Case study A to D	The targets were developed for the implemented projects using the defined procedure. Since the targets resulted in the aversion of energy-wastage events, it shows that they were not only effective but also feasible. Case Study D also highlights how the targets were easily updated and recalculated once they became unfeasible.
Technical objective: Point 2.	Case study A to D	The SMS notifications and user interface were used to monitor the projects in Case study A, B, and C. The SMS notification logs were used on Case study D.
Technical objective: Point 3 (Mitigating energy wastage).	Case study A	Two notable energy-wastage events were mitigated through the monitoring system. They saved the project over R96 000 due to the quick response.
Technical objective: Point 3 (Mitigating energy wastage).	Case study B	Energy-wastage events in load shift projects were mitigated in two notable incidents. The monitoring system saved the project approximately R5 300 and has the potential to mitigate energy wastage to the value of R200 000.
Technical objective: Point 3 (Mitigating energy wastage).	Case study C	Energy wastage in the form of loss of generation was mitigated on a notable incident. A negative cost impact of R11 304 was limited to R1 413 due to the quick response.
Technical objective: Point 3 (Project deterioration).	Case study A	The overall performance for the integration project was maintained for twelve months owing to the constant intervention due to the monitoring system. Interruptions to the project did not result in the deterioration of the project.
User engagement objective.	Case study D	The monitoring system ensured that each reported incident was of high importance and reduced the triggers being perceived as insignificant.

Chapter 4

Conclusion

4.1 Summary

The objective of this study was to develop a monitoring system which can efficiently track and mitigate energy-wastage events in implemented projects using targets. The need for such a system arose from the inability of the present monitoring tools to mitigate energy wastage in a timely manner. The system was developed to accurately model targets and baselines using data gathered from the mine data historian. These targets and baselines were implemented on an existing ESCo web-based platform and on a standalone SMS notification system. The monitoring system was implemented on a mining group to service the different project types.

Case Study A was a compressed air network integration project which involved Mine A and Mine B. The monitoring system was successful in mitigating energy wastage which arose from a compressor being utilised outside of the project scope. Two notable events occurred where the compressor at Mine A was switched on outside of the project scope; however, owing to the monitoring system, the potential combined loss of R96 000 was only limited to approximately R8 000. The monitoring system also helped in ensuring that the project did not deteriorate through constant intervention and guaranteed savings for a twelve-month period.

Case Study B involved a load shifting project implemented on Mine D. The monitoring system was successful in mitigating energy-wastage events arising from prematurely ending the load shift. Implementing the monitoring system on all the load shifting projects in the mining group has the potential of mitigating energy wastage to the value of R2-million annually.

Case Study C was a project on Mine D's turbine generator. It involved ensuring that the generator was always operational to make use of the available water to offset the electricity costs of the mine. The monitoring system was successful in mitigating energy wastage arising from the generator tripping and switching off. Due to the quick response, a negative cost impact of R11 304 was limited to R1 413 (an 87% reduction) as the mine did not have to purchase the electricity from nation's supplier, Eskom. An annual potential energy cost saving of R0.4-million is projected due to the intervention of the monitoring system. This case study also showed how versatile the monitoring system was with its ability to monitor maximum as well as minimum energy values.

Case Study D assessed the ability to promote user engagement and the evaluation of the implemented targets. This was to ensure that each SMS notification sent out was of high importance, reducing the possibility that the notifications would be perceived as insignificant. The generated logs allowed continuous evaluation of the triggered notifications to ensure unending efficiency.

Considering the above-mentioned results and case studies, the monitoring system was effective in mitigating energy wastage in a variety of implemented projects. This also indicates how versatile a tool it is, and that it has the potential to monitor any system in deep-level mines. It also helped to lower the time taken to respond to actions through its simplified but effective visual output.

In this study, the monitoring system was only implemented in a single mining group to primarily monitor energy. Through its versatility, it can be used to monitor other mining operations, such as flow and temperature, if they have data stored in a data historian. If implemented on more mining systems, it has the potential to continuously secure project energy savings as well as improve the general efficiency in the South African mining industry.

4.2 Limitations and recommendations for future work

Two limitations were identified with the help of the case studies and are summarised in the following sections. This gives scope to further improve the monitoring system in order to provide better efficiency.

4.2.1 Accounting for additional variables

Projects such as pumping load shift are dependent on additional variables such as the dam levels. The monitoring system only accounted for energy values extracted from the database; therefore, the energy values had no context. This caused a few false positives where the "energy wastage" was flagged in the pumping project, but the control operator would respond to inform the ESCo engineer that the dams were full.

In future, each pumping load shift project can be linked to the respective dam level to ensure that each event triggered is warranted. This will reduce the likelihood of a notification triggering when the dams are flooding.

4.2.2 A structured method to audit the SMS logs

The SMS notification logs were used as a metric to evaluate whether the targets should be recalculated. The targets were also recalculated according to the specific events which occur in the mine. Presently, there is no clear-cut approach to audit the logs, and this led to delays in the re-evaluation of the targets seen on Case Study C.

In future, a structured auditing approach will be proposed to also track the frequency of triggered notifications. This will reduce the turnaround time in identifying instances where the monitoring system outputs are perceived as insignificant. This will further improve user engagement and efficiency.

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