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Investigating the financial impact of energy losses due to pump efficiency degradation in South African deep mines

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ABSTRACT

The high operational cost associated with electricity consumption is a growing concern for deep-level mines in South Africa. The mines use high-demand equipment like pumps, compressors, ventilation fans and refrigeration plants to maintain safe working conditions in the mine. One of the key operational components of deep-level mines is the pumping system. Due to the extreme depths of these mines, high-performance pumps are required to dewater the mines. The high volumes of water being pumped from these extreme depths make the pumping systems one of the largest electricity consumers in the mines. Due to the high reliability of the multistage pumps used in the mining industry, little attention is given to the efficiency degradation of these pumps. The degradation rate of pumps is dependent on multiple factors and is therefore nearly impossible to predict. The degradation of pumps increases the electricity consumption of the pumps since the conversion from electrical energy to hydraulic energy becomes less efficient. More electricity consumption leads to higher operational costs for the pumps. Improving the effectiveness of water and energy use is a key objective for the mining industry in a time of high energy costs and growing sustainability concerns. The need to investigate the financial losses that occurred as a result of pump efficiency degradation becomes clear.

A quantitive technical financial research study was conducted to determine the financial losses that occurred as a result of pump efficiency degradation. Primary pump performance data was gathered from the mine over a period of three years. A data-driven time series forecasting model was developed to determine the baseline operational cost of a pump station in a well-known deep-level gold mine in South Africa. The prediction model was developed from the information gathered from the baseline model, to predict the operational cost of the pump station, had the pumps been refurbished to the original efficiency. The two models were compared, to determine the financial losses incurred due to pump efficiency degradation. A total of R 3 million was lost over three years as a result of pump efficiency degradation of the nine pumps within the analysed pump station.

From the results, it is clear that it is beneficial for companies to do condition monitoring on pumps, not only just for failure prediction, but also for monitoring financial losses. The least efficient pump in the pump station accumulated 50% of the refurbishment cost in only three years. The pump has been in operation for 18 years and was only utilised 7%

in the three years. Therefore it can be estimated with a high level of confidence that the pump’s energy losses have far exceeded the refurbishment cost of the pump. It is recommended that deep-level mines implement performance measurement strategies on pumping stations, as significant financial losses can go unnoticed. The results from performance measurement can be used to improve maintenance strategies and pump scheduling. The financial losses relating to pump efficiency degradation will only become more significant with time, as efficiency decrease over time, and energy tariffs increase.

KEYWORDS: Pump efficiency degradation, pump performance monitoring, energy efficiency, deep-level mines, pumping system improvement, predictive maintenance

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ABBREVIATIONS

3-CPFS	Three Chamber Pump Feeder Systems
BAC	Bulk Air Coolers
DSM	Demand Side Management
EEM	Demand Side Management
GDP	Gross Domestic Product
h	Hours
km	Kilometre
kPa	Kilopascal
kW	Kilowatt
kWh	kilowatt-hour
Ml	Megalitre
MPa	Megapascal
MW	Megawatt
m	meter
MCS	Mine Cooling System
QLFS	Quarterly Labour Force Survey
R	Rand
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-use

CHAPTER 1 NATURE AND SCOPE OF THE STUDY

1.1 Introduction

High operating costs are a major concern for South African mines, which can lead to a reduction in mine life (Maregedze *et al.*, 2022:2). The electricity cost makes up approximately 20% of the operating cost of a deep-level mine. The high electricity cost associated with mining operations remains a concern for mines operating on narrow profit margins. The high operational cost associated with electricity prices in South Africa is the primary reason why mining operations are declining (Neingo & Tholana, 2016:283).

Due to the high volumes of water collected underground, the mine must be dewatered to continue mining operations. The dewatering process is a necessity for the continuous operation of the mine, and therefore needs to be controlled efficiently. The dewatering process ensures the water levels of the cooling system are maintained and prevents the mine from flooding. The dewatering system uses multiple high-performance pumps to dewater the mine (Groenewald *et al.*, 2013:1-4). The world's largest hydraulic heads are found in South African gold mines. The high hydraulic heads and high volumes to be dewatered place additional strain on deep-level mines, due to the high electricity consumption associated with pumping systems (Winde *et al.*, 2017:679).

Due to the reliability of multi-stage centrifugal pumps, little information is known about performance changes during the pump's operation (Eaton *et al.*, 2018:1). Over the lifetime of the pump, the inefficiencies will decrease and result in increased long-term costs. The performance decrease is usually realised once a significant reduction in performance affects the whole system driven by the pump. The most prominent attribute to the decrease in pump performance; is a pump's degradation over time, yet; no adequate relationship has been developed between the two (Eaton *et al.*, 2018:1).

Improving the effectiveness of water and energy use is a key objective for the mining industry in a time of high energy costs and growing sustainability concerns (Vosloo *et al.*, 2012:328). An adapted bottom-up energy efficiency and saving calculation to predict possible energy savings is possible by determining energy losses (Reichl & Kollmann, 2011:423). Therefore, research regarding the financial impact of energy losses due to pump efficiency degradation in South African deep mines is required

1.2 Background of the study

The backbone of the South African economy is the mining industry, who employs more people directly and indirectly than any other economic sector. The largest contributor to the country's Gross Domestic Product (GDP) is the mining industry, who contributes approximately 7.5% to the GDP (Khubana, 2021:1). The mining industry's contribution to the GDP decreased by 3.2% in the fourth quarter of 2021, 2.1% in the first quarter of 2022, and 3.5% in the second quarter of 2022 (Stats-SA, 2022a:9). Stats-SA (2022b:3) stated in the Quarterly Labour Force Survey (QLFS), that the mining industry employs 406 000 people. South Africa has at least 8.0 million unemployed people. The official unemployment rate decreased by 0.6% in the second quarter of 2022 to an unemployment rate of 33.9% (Stats-SA, 2022b:9). The decrease in mining activity, will not only have a negative impact on the country's GDP, but also the unemployment rate of South Africa.

A global downward trend in terms of productivity and a return on capital invested is experienced in the mining industry of approximately 4% per annum, with a reported 30-year low in 2015 (McKinsey, 2017:4). In July of 2022, South Africa's mining production was down 8.4% year-on-year, following downwardly revised 7.1% drops in June and market forecasts of a 5% decline (TradingEconomics, 2022). It is clear from the trajectory of the production decline that the South African mining industry faces an uncertain future.

The South African mining industry is a large consumer of electricity; consuming more than 10% of the country's generated electricity (Ratshomo & Nembahe, 2019:36). The gold mines are the highest consumer of electricity across the mining sector; consuming almost as much as all the other mining sectors combined (Mare *et al.*, 2016:112-117).

Eight of the world's ten deepest mines are gold mines situated in the Witwatersrand basin in South Africa. Anglo Gold Ashanti's Mponeng Gold Mine is currently the deepest mine, with operations ranging between 2.4 and 3.9 km below the surface (Nex & Kinnaird, 2019:32). One of the biggest challenges of these extreme depths is the high underground temperatures. The temperatures increase significantly as the depth of the mine increase.

At these extreme depths, the virgin rock temperatures can reach up to 55ºC. These high rock temperatures increase the air temperatures in the mine (Groenewald *et al.*, 2013:2). Significant Mine Cooling Systems (MCSs) are required to operate a mine at such extreme depths. The MCSs are used to ensure the underground working conditions in the mine are below the legal limit of 32ºC wet bulb, consisting of water reticulation (pumping) and refrigeration sub-systems. The MCSs consume approximately 41% of the total electricity supplied to deep-level mines (Maré, 2017:4).

Approximately 3.4 Mega Watt (MW) of electrical power is required to dewater 1 Megalitre (Ml) of water from a depth of 1 000 meters (m) in one hour (h); if the pumps operate at 80% efficiency. Some gold mines in South Africa are 4 000 meters (m) deep and dewater more than 20 Mega Litre (Ml) of water per day (De Lange, 2006:2). Pumping systems consume approximately 14% of the electricity supplied to the mining industry (Groenewald *et al.*, 2013:1-4).

The preceding sections indicate that South African deep mines face sustainability challenges as a result of the high operational cost associated with high energy consumption, especially the dewatering systems. The depts of the mines require high energy consumption pumps to maintain the continuous operations within the mines.

The most popular pumps for fluid transfer in many industries and other sectors are multistage centrifugal pumps (Walker, 2013:50-54) (Jafarzadeh *et al.*, 2011:242-249) (Hall, 2010:31). Multi-stage centrifugal pumps are mainly used in deep-level mines due to the high static head created by the extreme depths (Schoeman, 2014:31). Deep mines use large multistage clear water pumps driven by constant-speed electric motors as the primary means of dewatering (Schoeman, 2014:31). . Due to their flexibility and durability, multistage centrifugal pumps are intended to withstand more demanding environments. Multistage centrifugal pumps that have recently been developed are built with better wear resistance and increased availability (Schoeman, 2014:32).

Pump efficiency degradation is caused by pump wear. The amount of internal wear that a pump can tolerate depends on the kind of pump and the system characteristics it operates in. There are many types of wear that can occur inside a pump like wear on impeller outer ends, internal component wear, nodular growths, cavitation, blockage, casing corrosion, impact damage, leaking external seals and maintenance errors (Beebe

& Beebe, 2004:24). . Pumps with high specific speeds exhibit a much smaller relative power increase as a result of internal wear, but the energy increase may still be substantial due to the size of these pumps (Beebe & Beebe, 2004:28).

A multistage centrifugal pump has a 15-year expected lifespan. If the necessary maintenance is carried out, the normal life of a pump can be extended by up to 15%. This can reduce the amount of electrical energy used by up to 7%. If the power consumption rises while the discharge flow remains constant, a pump should be considered for refurbishment. A decreasing efficiency is indicated by increased power consumption. Lower efficiency means that the pump will need to run for longer to move the same amount of fluid. Performance monitoring and condition monitoring of a pump can indicate when a pump should be refurbished (Oberholzer, 2015:16).

Good quality data, such as that obtained by carefully executed tests, is required for condition monitoring. However, once repeatability is established, a plant's permanently installed instrumentation frequently provides a wealth of useful information (Beebe & Beebe, 2004:7). Performance monitoring is less well known, but it makes it possible to determine the best time to restore performance when a machine's condition deteriorates; resulting in higher energy consumption. . If the repeatability of the monitoring parameters is demonstrated to be sufficiently narrow, permanently installed plant instrumentation may occasionally be used to monitor equipment performance (Beebe & Beebe, 2004:9).

Eskom has taken steps to intensify electricity rationing through load shedding and a range of tariff increases (Ateba *et al.*, 2019:1324). The electrical tariffs have been on a steep increase since 2007. The average electricity price increased by approximately 460% from 2007 to 2020, when not considering inflation. If inflation is taken into account, the average increase is still around 180% (Labuschagne, 2020).

Improving the effectiveness of water and energy use is a key objective for the mining industry in a time of high energy costs and growing sustainability concerns (Vosloo *et al.*, 2012:328). Various authors have proposed energy efficiency strategies for pumping systems, including maintenance and online monitoring, assessment and reporting, and design and calibration (Torregrossa *et al.*, 2017:1431). A range of methods used to forecast the outcome of a potential Energy Efficiency Measure (EEM) application is referred to as prediction. The outcomes of the predictions are then utilized to formulate the best energy retrofitting scenarios and to advocate the usage of some EEMs over others. The prediction technique is an adapted bottom-up energy efficiency and saving calculation (Grillone *et al.*, 2020:3). An adapted bottom-up energy efficiency and saving calculation to predict possible energy savings is possible by determining energy losses (Reichl & Kollmann, 2011:423). Therefore, research regarding the financial impact of energy losses due to pump efficiency degradation in South African deep mines is required

1.3 Problem statement

As more pressure is placed on mining companies by the increase in electricity costs, operational costs have to be reduced to ensure sustainability (Neingo & Tholana, 2016:283). Since pumping is a crucial function of complex mining operations, it is considered an operational requirement regardless of cost. Mining operations can not continue without dewatering the mine (De Lange, 2006:2). Pumping systems can contribute as much as 20% to the total electricity consumption of a deep-level mine (Maré, 2017:4).

The various departments within mining operations focus on different aspects of the business. The operation department focuses on achieving operational targets, while the financial department focuses on reducing capital expenditure to increase profit margins. Little to no interdepartmental collaboration exists between technical departments and financial departments to collaboratively reduce operational costs while achieving operational requirements (Beebe & Beebe, 2004:3). A possible focus area to reduce operational costs while maintaining operational requirements is to investigate the financial losses that occur due to pump efficiency losses.

Existing research focuses on pump scheduling, Demand Side Management (DSM) initiatives, and load shift initiatives to reduce pumping operational costs in deep mines (Vosloo, 2008:5). No research exists to determine the financial impact of energy consumption change due to pump efficiency reduction in deep-level mines. Therefore, there is a need to investigate the financial losses occurring in deep mines, caused by energy losses as a result of pump efficiency degradation.

1.4 Objectives of the study

The primary objective of the study is to determine the financial impact of energy losses due to pump efficiency degradation in deep mines. This was achieved by evaluating the operational cost associated with energy consumption increase as a result of pump efficiency degradation in a South African gold mine.

The primary objective of the study was satisfied by satisfying the secondary objectives. The secondary objectives of the study are listed below:

To determine how a pump’s efficiency degradation is measured, the existing literature was reviewed, to determine the methods used to calculate pump efficiency. The technical aspects relating to pump efficiency calculations were researched and analysed, to calculate the efficiency degradation of the pumps. The technical aspects relating to pump efficiency calculations are presented in Chapter 2.

To determine the correlation between pump efficiency degradation and electrical energy consumption, the existing literature reviewed in Chapter 2 was applied to develop mathematical models that indicated the relationship between the two variables.

To calculate the financial losses incurred as a result of pump efficiency degradation, an energy-saving prediction model was developed as prescribed by the literature in Chapter 2. A time series forecasting model was used to develop baseline models and prediction models were used to calculate the gross financial losses incurred. The analyses are presented in Chapter 4.

1.5 Research questions

The research questions were formulated and had to be answered to satisfy the objectives of the study. The research questions are stated below:

- What variables have to be measured to determine pump efficiency degradation?
- How are the measured variables used to calculate pump efficiency degradation?
- How does pump efficiency degradation relate to energy consumption, and how can it be determined?

- How can the financial losses of pump efficiency degradation be determined?

1.6 Scope of the study

The study aimed to determine the financial losses that occurred as a result of pump efficiency degradation. The study was only conducted on a single pump station in a South African deep mine. The pumping system operates at a fixed head, and therefore dynamic pumping systems were not considered in this study. The operational conditions of dynamic pumping systems change continuously and are therefore not applicable to this study. Even though the study was conducted on a deep-level gold mine in South Africa, the methodology can be applied to other applications with similar operating conditions like other deep-level mines, pumping schemes and high-rise buildings.

1.7 Research methodology

Five major research paradigms or philosophies exist in management and business research: interpretivism, positivism, pragmatism, postmodernism, and critical realism (Saunders *et al.*, 2016:135). However, (Collis & Hussey, 2013:43) indicates that the most dominant research paradigms or philosophies in the field of management and social sciences are interpretivism and positivism. Primary scientific data was analysed using empirical analysis to achieve the primary and secondary objectives of the study. The empirical analysis was done without any bias or human interpretation, and therefore the research paradigm of the study followed a positivism paradigm.

The deductive research approach proceeds from the general to the particular by deriving a hypothesis or hypotheses from a theory and then testing the hypotheses and improving the original theory (Woiceshyn & Daellenbach, 2018:185). Any theoretical base can be used to start the deductive research approach. The theoretical base is used to deduce any number of hypotheses (Woiceshyn & Daellenbach, 2018:186). The process of deductive research is shown in Figure 1-1 (Pearse, 2019:264). This paradigm favours unbiased research that examines an organization from the outside. This study sought to examine the effects of energy losses from an external viewpoint without bias.

The outcome of a quantitative research study can be reached by analysing numerical data collected during the study. Analysing data aims to reveal underlying trends, patterns and relationships among variables in the study's context (Albers, 2017:1). The methodological choice for this study is a quantitative research choice since the research paradigm is positivistic and numerical data was collected. The research choice can be better defined as technical/financial because the primary information is numerical values obtained from instrumentation measurements. The primary data was analysed and developed into a mathematical model to test the predetermined hypothesis. The secondary data is financial data used as variables in the mathematical model to satisfy the study's primary objective.

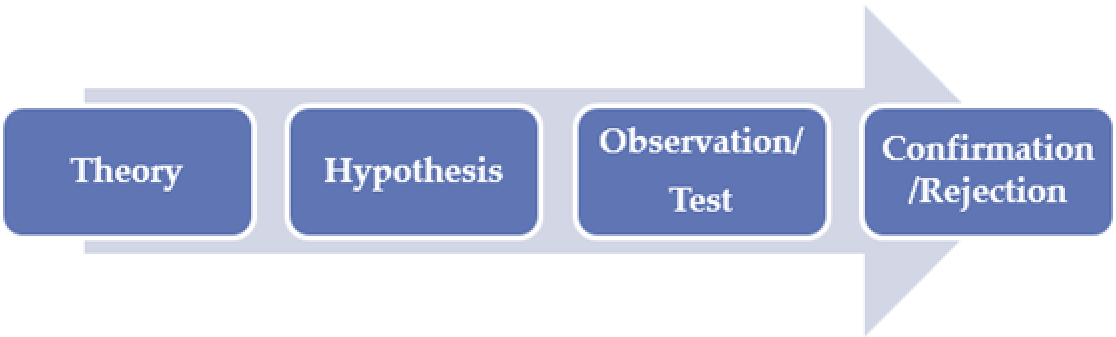


Figure 1-1: The process of deductive research

(Pearse, 2019:264)

1.8 Contribution of the study

The study contributes to literature relating to energy improvement initiatives in the deep-level mining industry. Improving the effectiveness of water and energy use is a key objective for the mining industry in a time of high energy costs and growing sustainability concerns (Vosloo *et al.*, 2012:328). The study revealed that basic performance measurement data can be utilised to monitor pump efficiency degradation. The financial losses incurred as a result of increased energy consumption are not only linked to the rate of pump efficiency degradation but also the increase of electricity tariffs and the utilisation of individual pumps in pump stations. The study revealed that even though a pump’s performance meets the operational requirements of the application, it is not necessarily financially feasible to operate the pump any longer. This phenomenon contributes to the literature on predictive maintenance strategies. A comprehensive predictive maintenance strategy will not only consider the equipment condition, but also the operational cost based on performance. The contribution of this study will become increasingly relevant if the electricity tariffs in South Africa increase at the same trend they did in the past 10 years.

1.9 Ethical considerations

During the study, various ethical issues were anticipated. Ethical risks were mitigated to ensure that no ethical lines are grossed that can cause harm to an individual, a group or an organisation. These ethical issues occurred throughout the study and had to be dealt with at each level of the study. The topic was chosen as a technical study that does not disclose any company secrets like production data. The study was completed without disclosing non-public information that can cause the company harm or give competitors an advantage. The topic was selected so that the study could be done at any mine and not have to be from a specific mine or company. The ethical issues involved with the accessibility of the data were anticipated, and the ethical risks were mitigated before the study started. The data is not publicly available and had to be accessed directly from the mine's data servers. The mine formally approved the collection and publishing of the data required to complete the study. The naming convention of the data was changed to descriptive generic names to ensure the company is not disclosed in any way. The data was not compromised in any way when changing the description of the data sets. No company-specific information is visible in the data. The images containing company information were altered to conceal the identity of the mine.

1.10 Definition of key concepts

Mare *et al.* (2016:18) stated that deep-level mines are generally defined in the mining industry as mines deeper than 1.5 kilometres (km).

Fissure water is defined by Vosloo (2008:11) as natural underground water that seeps through the subsurface rock.

Mine water or service water is water that is used during mining operations like drilling, washing and dust suppression (Vosloo, 2008:148).

The term pump efficiency refers to how efficiently the electrical power supplied to the pump motor is converted to hydraulic energy in the water. The higher the pump's efficiency, the more water will be pumped at a fixed pressure with lower energy consumption (Thin *et al.*, 2008:425).

Condition monitoring involves continuously monitoring an operational asset, analysing the data gathered, identifying signs of degradation, diagnosing causes of faults, and predicting how long the asset can be used safely or economically (Beebe & Beebe, 2004:5-6).

1.11 Layout of the study

Chapter 1 provides the background information on the study. The background information consists of the nature and the scope of the study, including the study objectives and the importance thereof, the research methodology and the contributions of the study.

Chapter 2 consists of a detailed literature review regarding the variables that impact the financial losses of pumps in the deep-level mining industry due to energy losses caused by pump efficiency degradation. The literature study will focus on the relevant theories, concepts and calculations relating to the energy losses caused by pump efficiency degradation.

Chapter 3 provides information on the research design. The research design consist specifies the details of the research methodology followed during this study. The research methodology consists of a literature review, research paradigm, research approach, methodological choice, measurement instrument, data collection, sampling and data analysis.

Chapter 4 contains a detailed data analysis and a theoretical model that gives a theoretical baseline to determine the financial impact of energy losses due to the efficiency degradation of pumps. The results were critically discussed to achieve the objectives of the study.

Chapter 5 summarises the results and various scenarios of the theoretical baseline model to simulate multiple operational conditions from which recommendations can be made, and an improved operational and maintenance schedule can be developed.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The South African mining industry is a large consumer of electricity, consuming more than 10% of the country's generated electricity (Ratshomo & Nembahe, 2019:36). Gold is an important economic driver in South Africa (Vosloo, 2008:7). The gold mines are the highest consumer of electricity across the mining sector, consuming almost as much as all the other mining sectors combined (Mare *et al.*, 2016:112-117).

Due to the high volumes of water collected underground, the mine must be dewatered to continue mining operations. The dewatering process is a necessity for the continuous operation of the mine, and therefore needs to be controlled efficiently. The dewatering process ensures the water levels of the cooling system are maintained and prevents the mine from flooding. The dewatering system uses multiple high-performance pumps to dewater the mine (Groenewald *et al.*, 2013:1-4).

Approximately 3.4 Mega Watt (MW) of electrical power is required to dewater 1 Megalitre (Ml) of water from a depth of 1 000 meters (m) in one hour (h); if the pumps operate at 80% efficiency. Some gold mines in South Africa are 4 000 meters (m) deep and dewater more than 20 Mega litres (Ml) of water per day (De Lange, 2006:2). Pumping systems consume approximately 14% of the electricity supplied to the mining industry (Groenewald *et al.*, 2013:1-4).

Over the lifetime of the pump, the inefficiencies will increase and result in increased long-term costs. The performance decrease is usually realised once a significant reduction in performance affects the whole system driven by the pump (Beebe, 2012:34-40). The most prominent attribute to the decrease in pump performance; is a pump's degradation over time, yet; no adequate relationship has been developed between the two (Cox, 1955:129-157).

The electrical tariffs have been on a steep increase since 2007. The average electricity price increased by approximately 460% from 2007 to 2020, when not considering inflation. If inflation is taken into account, the average increase is still around 180% (Labuschagne, 2020:2).

Due to the increase in electricity prices, and the energy losses associated with pump degradation, a need for improved energy management on pumping systems arise in the field (Vosloo *et al.*, 2012:328).

2.2 Deep mines in South Africa

2.2.1 Overview

It is crucial to understand the different types of mining operations in South Africa and distinguish between them. The mining methods in South Africa vary widely, based on the type of mineral resources and their location. South Africa has two main types of mining, namely underground mining and surface mining (Ochieng *et al.*, 2010:3352). Only a limited amount of literature distinguished between deep-level and underground mines. Maré (2017:VXiii) defined a mine that is more than 1.5 km below the surface as a deep-level mine.

Most of South Africa's deep-level gold mines are situated in the Witwatersrand goldfields, also known as the Witwatersrand Basin. The deepest excavations in the world are the gold mines located in the Witwatersrand basin, with future excavations planned to reach 5000m below the surface (Grodner, 2001:885). The gold mines in this area have the highest gold yield in the country (Fuchs *et al.*, 2016:151). The gold concentration in the Witwatersrand goldfields is displayed in Figure 2-1. This information serves as background information regarding the location of the deep-level gold mines in South Africa, which will link to the depths of mines.

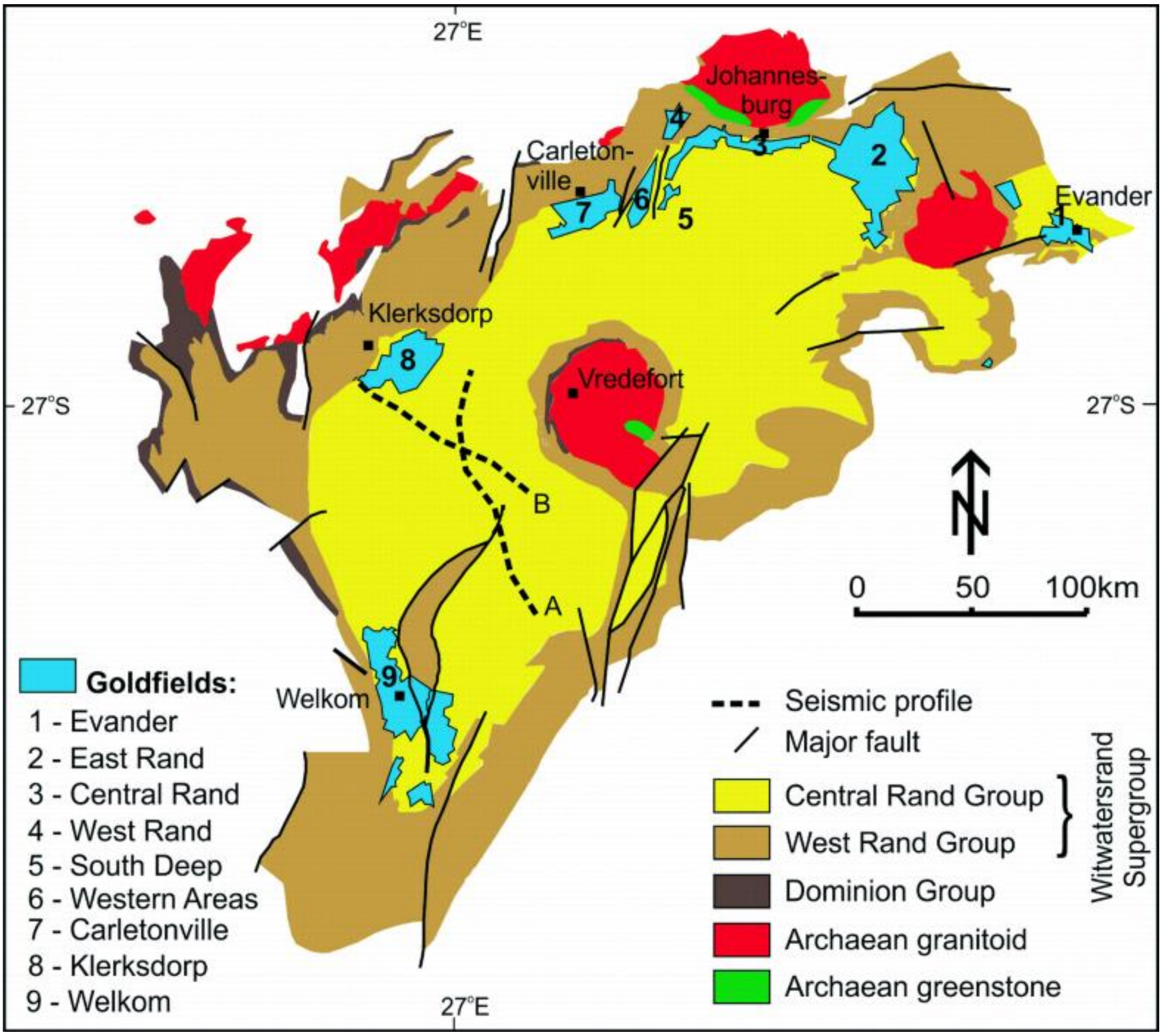


Figure 2-1: Simplified geographical layout of the Witwatersrand basin

(Kröner & Hofmann, 2019:257)

One of the biggest challenges of these extreme depths is the high underground temperatures. The temperatures increase significantly as the depth of the mine increase. Mponeng mine, located near Carltonville in the Witwatersrand basin, is currently the deepest gold mine globally, reaching 3778m below the surface. At these extreme depths, the virgin rock temperatures can reach up to 55ºC. These high rock temperatures increase the air temperatures in the mine. Human physiology cannot tolerate these levels without intervention. (Groenewald *et al.*, 2013:2). These high temperatures pose a significant challenge; maintaining a comfortable surrounding temperature for man and machine (Calitz, 2005:9). Significant Mine Cooling Systems (MCSs) are required to operate a mine at such extreme depths. The MCSs are used to ensure the underground working conditions in the mine are below the legal limit of 32ºC wet bulb, consisting of water reticulation (pumping) and refrigeration sub-systems. The MCSs consume approximately 41% of the total electricity supplied to deep-level mines (Maré, 2017:4). The percentage of electricity consumed by each commodity in a mining group's deep-level gold mines is illustrated in Figure 2-2:

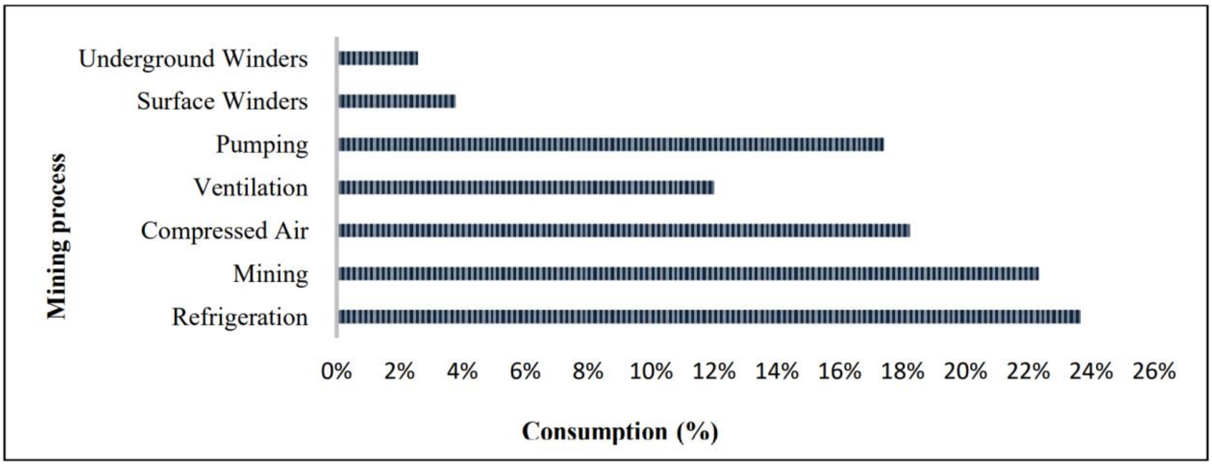


Figure 2-2: The percentage of electricity consumed by each mining commodity

(Maré, 2017:4)

2.2.2 Mine water reticulation

The water used in deep mines for cooling and mining operations is transported down the mine and removed again to ensure continuous operation. The water cycle forms part of the mine's water reticulation (Oberholzer, 2015:4).

As discussed in the previous section, Mine Cooling Systems (MSCs) are required to maintain comfortable temperatures underground. The best cooling method used in deep mines is through large refrigeration plants, which feed large volumes of chilled water underground for cooling purposes. These refrigeration plants are located on the surface, but due to the extreme depths of some of the mines, there are also plants underground. The water fed through the refrigeration plants is usually pumped from underground; however, water may be procured from external sources if additional water is required (Vosloo, 2008:8). Figure 2-3 illustrates a schematic representation of a typical refrigeration plant reticulation.

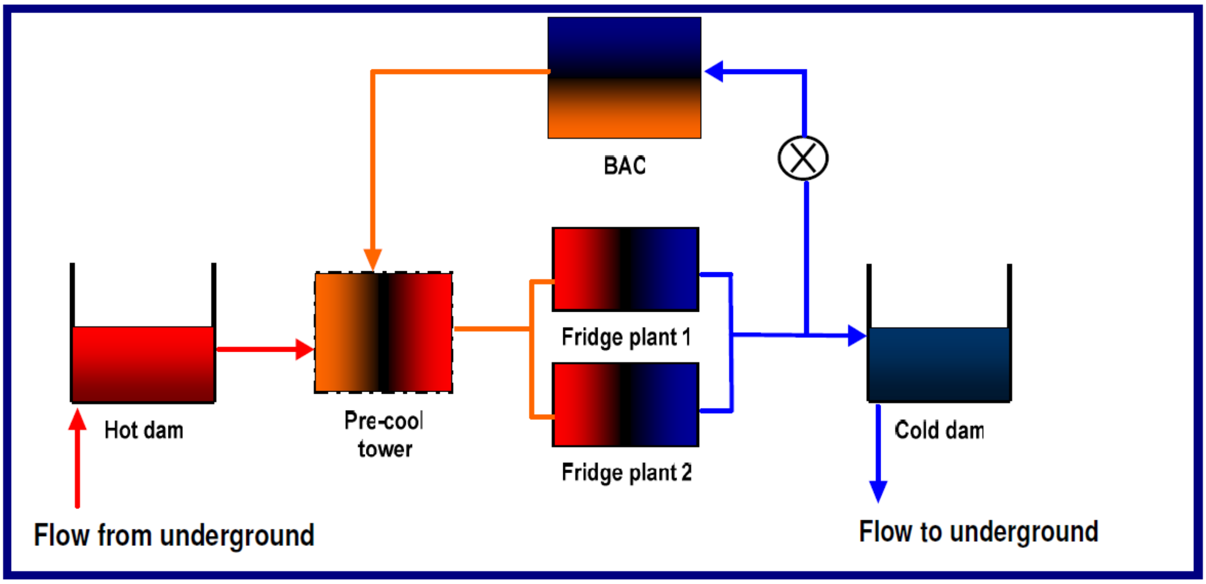


Figure 2-3: A schematic representation of a refrigeration plant reticulation

(Vosloo, 2008:8)

As the mining and system needs vary from day to day, so does the chilled water demand in the deep mine. The cost of using chilled water is generally minimised by reusing it because if more water is required, potable water has to be purchased (Schoeman, 2014:21). The basic water reticulation of a deep mine can be explained by referring to Figure 2-4.

Warm water is transferred via pumps from underground to a hot water dam on the surface at a temperature of approximately 28ºC, indicated by A in Figure 2-4. This hot water is then pre-cooled to 15ºC - 20ºC by cooling towers, indicated by B, which uses ambient air for cooling. After the water has passed through the cooling towers, it is fed through the fridge plant, indicated by C Figure 2-4, where it is cooled to the desired temperature of 3ºC to 4ºC (Vosloo, 2008:9). The water is used as a cooling medium and transported to underground levels (Calitz, 2005:13).

A portion of the cooling water fed to the underground levels is sent through Bulk Air Coolers (BAC), indicated by D in Figure 2-4, cooling cars and spot coolers to cool down the surrounding air (Vosloo, 2008:11). Surface BACs are the primary component of the air cooling system (Oberholzer, 2015:3). The chilled water fed through the BAC cools the air which is forced down the shaft by the primary ventilation fans (Prinsloo, 2004:22).

Before the water is transported to the secondary cooling system, the energy can be harvested from the water. As chilled water is sent down the shaft in a column, the pressure increases to approximately 10 Mega Pascals (MPa) (depending on the mine's depth). Energy can be generated by harvesting this pressure and converting it to energy for use in energy recovery systems, as indicated by E in Figure 2-4 (Schoeman, 2014:22).

Underground BACs are the secondary components of the air cooling system (Oberholzer, 2015:3). Their operation is similar to the surface BACs, but they are installed underground to re-cool the air-cooled by the surface BACs (Van der Walt & Whillier, 1978:111). Underground BACs are usually installed when a depth of 2000 m is exceeded (Oberholzer, 2015:3). When the cooled air is deeper than 1300 m from the last BAC, tertiary cooling is usually required (Biffi & Stanton, 2008:244). The ambient temperature closer to the working areas in haulages and stopes is cooled using cooling cars and spot coolers (Botha, 2010:10). Air is directed in a specific direction to cool a particular area (Oberholzer, 2015:3).

After the water passes through the cooling cars and spot coolers, it falls on the ground (footwall) and travels back to the hot water circuit, indicated by F, by entering underground settlers, indicated by G in Figure 2-4 (Schoeman, 2014:22). A significant portion of the cold water is fed to the cold water dam, which supplies cold water to various levels underground. The water provided from the refrigeration plant to underground levels is used by the cooling cars, and spot coolers, as well as rock drills and cleaning (sweeping). During the drilling and cleaning operations, the water ends up on the ground (footwall) and travels to an underground settler (Vosloo, 2008:11). The clean water from the settlers is sent to hot water dams to be pumped by the dewatering system, indicated by H in Figure 2-4 (Schoeman, 2014:22).

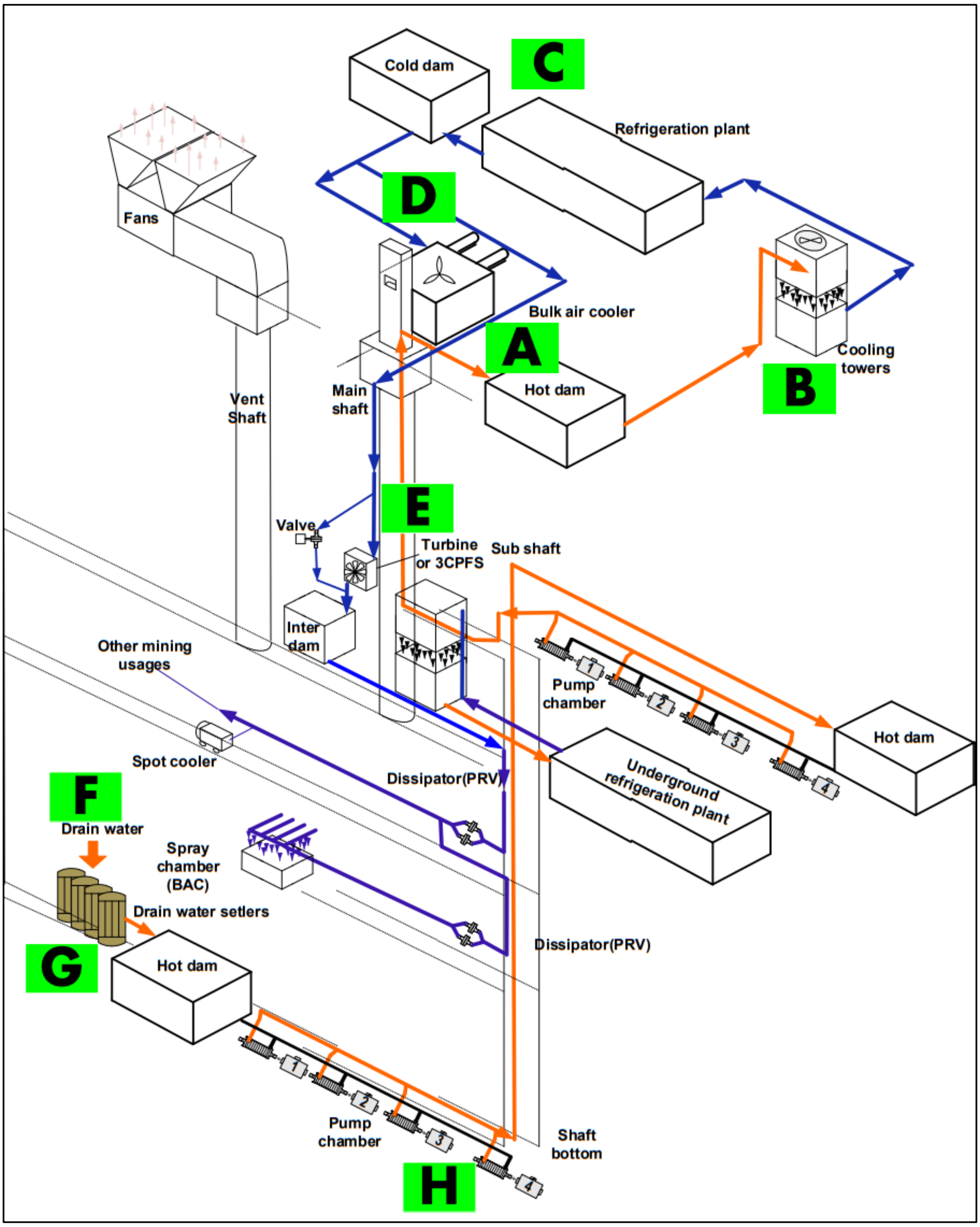


Figure 2-4: The basic water reticulation of a deep mine

(Schoeman, 2014)

2.2.3 Underground water in deep mines

Natural underground water (fissure water) seeps through the rocks and ends up on the ground (footwall) of the mine. The fissure water flows to the underground settlers and adds to the total water collected by the settlers (Vosloo, 2008:11). In some mines, the fissure water is collected separately from the mine water.

2.2.4 Dewatering of the mine

Water is required for multiple applications to ensure sustainable and safe mining. The water in the mine must be removed to ensure continuous operations and prevent the mine from flooding. The mines utilise dewatering systems to remove the water from the mine (Oberholzer, 2015:5). Fissure water and service water in collection dams at the bottom of deep mines are removed with dewatering systems (Botha, 2010:5). The service water that ends up on the floor (footwall) after it passes through the cooling systems and is utilised by the mining operations; gravity feeds through trenches to settlers at the shaft bottom (de la Vergne, 2003:189). The settlers remove the solid particles (slimes) from the water and send the clean water and mud slurry to the respective reservoirs for dewatering (Oberholzer, 2015:5). Dewatering is done with an upward cascading method to overcome the static head. The hot water is pumped from the hot water collection dam at the pump station near the shaft bottom to a hot water collection dam of a pump chamber at a higher level. The vertical distance can be up to 1380 m between two pump chamber collection dams (Oberholzer, 2015:5). The components of the dewatering system is illustrated in Figure 2-5.

Dewatering in deep mines is done with three methods, namely, pumps, Three Chamber Pump Feeder Systems (3-CPFS) and hydropower turbines (Oberholzer, 2015:8)

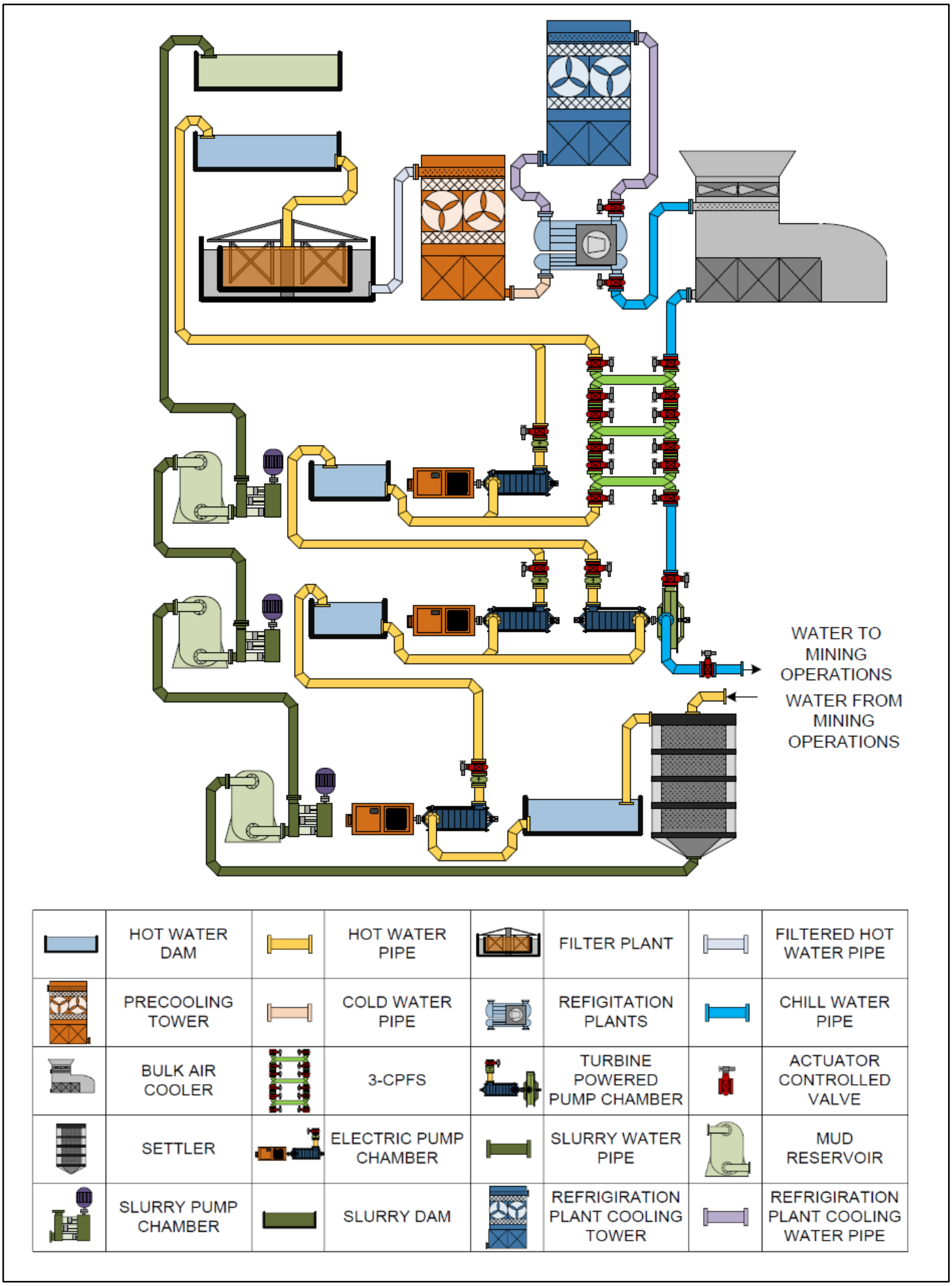


Figure 2-5: The components of the dewatering system

(Oberholzer, 2015)

Deep mines use large multistage clear water pumps driven by constant-speed electric motors as the primary means of dewatering (Schoeman, 2014:31). Figure 2-6 displays a typical motor and pump configuration. The extreme depth of the mines results in a high static head that needs to be overcome; therefore, multistage centrifugal pumps are primarily used.

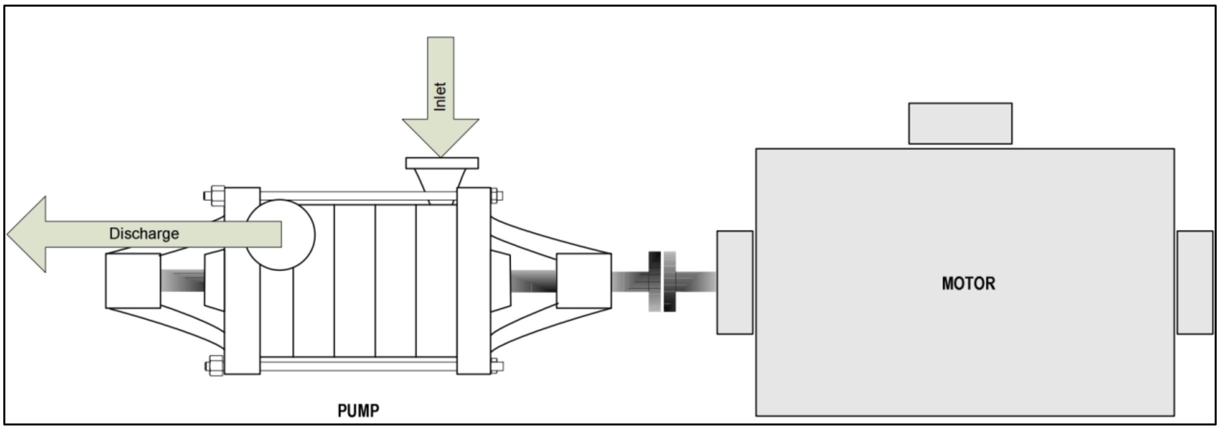


Figure 2-6: A typical motor and pump configuration

(Schoeman, 2014:31)

Pumps located on an underground pump station are configured to operate in parallel because of the varying inflow and discharge demand of holding dams, which ensures that outflow can be varied by stopping or starting a pump. In addition, this provides flexibility and redundancy by permitting independent pumps to pump into different discharge columns as required (Schoeman, 2014:32). Figure 2-7 displays a typical pump chamber with a parallel configuration and an upward cascading system.

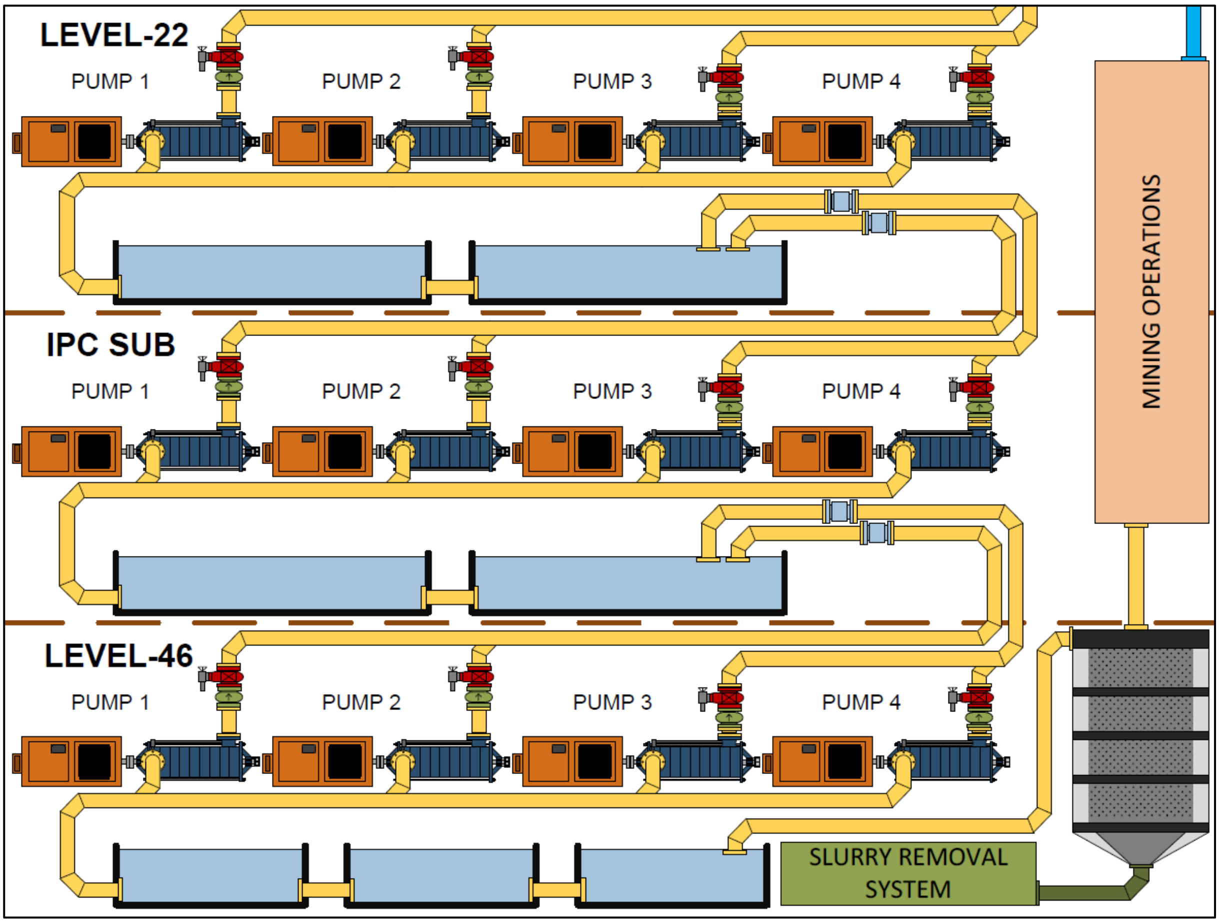


Figure 2-7: A typical pump chamber with a parallel configuration and an upward cascading system

(Oberholzer, 2015)

Due to the high electricity consumption of pumps, mines are using alternative methods to dewater the mine, like the 3-CPFS and hydropower turbines. By harvesting the potential energy of the service water entering the shaft, the 3-CPFS can pump clear hot water. The high-pressure chilled water transported down the shaft transfers the potential energy to the low-pressure hot water with valves and the basic principle of a U-tube (Rautenbach, 2004:5). A basic diagram of a 3-CPFS is displayed in Figure 2-8.

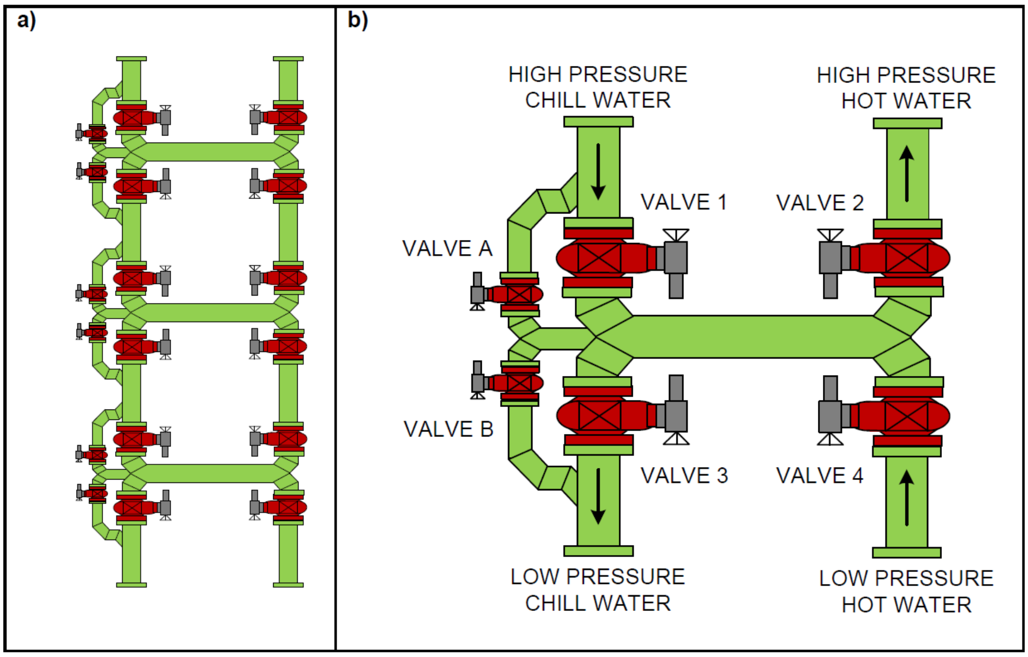


Figure 2-8: A basic diagram of a 3-CPFS

(Oberholzer, 2015)

Hydropower turbines are another alternative method of mine dewatering. Turbines have been installed on multiple shafts to harvest the service water's potential energy. The turbines are usually installed near underground pumping chambers. The turbine can be connected to a generator to generate electricity or to a multistage dewatering pump to dewater the mine. If a turbine is connected to a generator to generate electricity, the power is often applied to the dewatering system (Oberholzer, 2015)(9-10). The most common turbine used in the mines is a Pelton wheel as displayed in Figure 2-9.

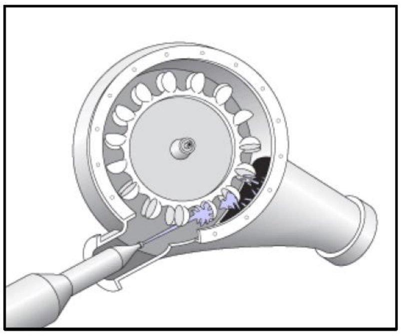
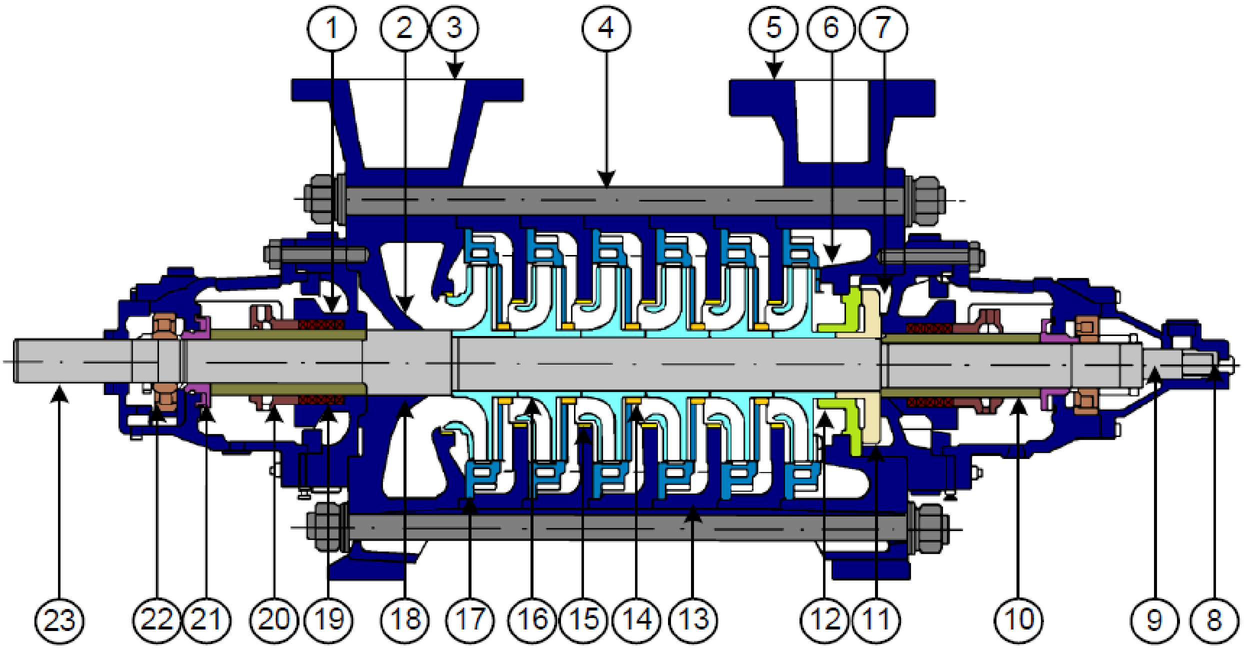


Figure 2-9: A representation of a Pelton wheel

(Oberholzer, 2015)

2.2.5 Dewatering pumps

The most popular pumps for fluid transfer in many industries and other sectors are multistage centrifugal pumps (Walker, 2013:50-54) (Jafarzadeh *et al.*, 2011:242-249) (Hall, 2010:31). Multi-stage centrifugal pumps are mainly used in deep-level mines due to the high static head created by the extreme depths (Schoeman, 2014:31). With a single-stage centrifugal pump, fluid velocity through a rotating impeller increases to generate a discharge pressure (Hall, 2010:33). The primary components of a centrifugal pump are the diffuser (volute) and the impeller. As illustrated by the water path in the pump, the operation of a typical multistage pump can be explained. The water enters the centre of the impeller from the pump inlet. The motor rotates the impeller to create a centrifugal force that forces the water through the volute passage resulting in increased water pressure and velocity (Schoeman, 2014:32). Multiple single stages make up a multistage centrifugal pump, where the outlet of the previous stage is connected to the inlet of the next stage. The first stage of the pump has an inlet for water, and the last stage has an outlet for the water to be discharged (Oberholzer, 2015:7). A segmental view of a multi-stage pump with its components is shown in Figure 2-10. Due to their flexibility and durability, multistage centrifugal pumps are intended to withstand more demanding environments. Multistage centrifugal pumps that have recently been developed are built with better wear resistance, increased availability, and lower maintenance costs in mind. The designs also facilitate maintenance, reducing the amount of time the pump is unavailable. The high electricity consumption of multi-stage pumps is one of their main drawbacks (Schoeman, 2014:32).



NR.	DESCRIPTION	NR.	DESCRIPTION
1	STUFFING BOX HOUSING	13	STAGE CASING
2	INLET CASING	14	WEAR RING
3	INLET	15	WEAR RING
4	ASSEMBLY FASTENER	16	IMPELLER
5	OUTLET	17	DIFFUSOR
6	OUTLET CASING	18	SHAFT
7	BALANCE DISC CHAMBER	19	PACKING
8	IMPELLER DISPLACEMENT	20	PACKING GLAND
9	PUMP NDE	21	O-RING
10	SHAFT SLEEVE	22	BEARING
11	BALANCE DISC	23	PUMP DE
12	BALANCE RING		

Figure 2-10: Segmental view of a multi-stage pump

(Oberholzer, 2015:52)

2.3 Pump performance characteristics

2.3.1 Overview

A pump can be considered simply as a machine that transfers liquid through a piping system while raising the pressure. Further definition of a pump is a machine that increases fluid pressure by utilising several energy transformations, as illustrated in

Figure 2-11. The energy input into a pump is usually the energy source utilised to power the driver. In most cases, it is an electric motor powered by electricity. Alternative forms of energy are used to power the driver like fuel to power a diesel or petrol engine, high-pressure steam to drive a steam turbine, compressed air to drive an air motor and high-pressure hydraulic fluid to power a hydraulic motor. Regardless of the driver's type, the driver's function is to convert the input energy into rotating energy at a constant speed, which serves as the input energy for the pump (Volk, 2013:1).

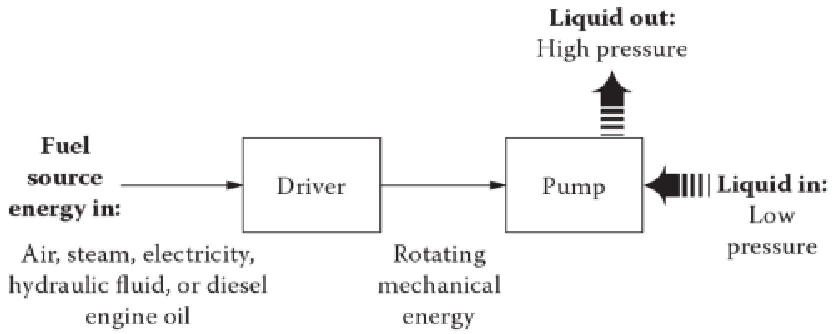


Figure 2-11: An illustration of energy transformation in a pump configuration

(Volk, 2013:2)

Three distinct reasons plus one related factor exist for raising the pressure of a liquid with a pump (Volk, 2013:2):

1. **Static elevation:** The pressure of a liquid must be increased to raise the liquid from one elevation to a higher elevation. This might be necessary for multiple purposes, like moving fluid from one floor of a building to a higher floor or pumping a liquid uphill.

2. **Friction:** It is essential to increase the fluid pressure to move it through a piping system while overcoming frictional losses. A liquid moving through a system of valves, fittings and pipes is subject to frictional losses along the way. These losses vary with the material and geometry of the valves, fittings and pipe, the density and viscosity of the liquid, and the flow rate.

3. **Pressure:** For some applications, a liquid's pressure is required to increase for process reasons. In addition to moving a fluid from a lower elevation to a higher elevation and overcoming friction, a fluid's pressure must sometimes be increased to

move it into a pressurised vessel, such as a fractioning tower, a boiler, or a pressurised pipeline.

4. **Velocity:** Not all the velocity energy is converted to pressure or potential energy in a pump. The outlet of most pumps is smaller than the pump's inlet, increasing fluid velocity between the outlet and the pump's inlet. The flow velocity must be considered when calculating a pump's total head.

The primary aspects that define a pump's performance are head, flow, power and efficiency (Beebe & Beebe, 2004:21). These parameters are further discussed in the sections to follow. Table 2-1 displays the terms, symbols and units generally used for the basic pump performance quantifiers. It is generally desirable to use volumetric terms for flow and manometric terms for head because the same head-flow curve applies for fluids at a range of temperatures if viscosity effects are neglected.). The power-flow curve will change in direct proportion to liquid density (Beebe & Beebe, 2004:21).

Table 2-1: Fundamental terms and units in pump performance

Quantity	Other terms used	Symbol	Units	Other units
Flow	Volumetric flowrate, Capacity, Discharge, Quantity	Q	m^3/l, L/s, m^3/h, Ml/d Sometimes kg/s	IGPM, USGPM
Head	Total head, Total dynamic head, Generated pressure, Generated head	H	m, kPa	Bars, ft, psi
Power	Power absorbed	P	W, kW	Hp
Efficiency		η	Decimal	%

(Beebe & Beebe, 2004:21)

2.3.2 Head and specific work

It is crucial to understand the relationship between head and pressure. Pressure is measured in units of kilopascal (kPa), kilograms per square centimetre (kg/cm2), or bar, whereas the equivalent unit for head is in meters (m). An important aspect of pump hydraulics is knowing that any pressure expressed in kPa refers to a static column of liquid expressed in meters. It does not mean that head and pressure are interchangeable terms because pressure is a force applied to an area, whereas head is a specific energy term (Volk, 2013:3).

The specific work Y of a pump is the total useful energy transmitted to the fluid per unit of mass. The work is measured between the discharge and suction nozzle of the pump. In practice, the head H is equal to the work Y divided by the gravitational acceleration g, expressed in equation 2.1. The head H displayed in equation 2.1 is also commonly termed as the total dynamic head (Gülich, 2008:47).

$$H = \frac{Y}{g} \qquad 2.1$$

Where:

$H = Head$

$Y = Work$

$g = Gravitational\ acceleration$

The total dynamic head has to be comprehended as a specific energy unit (or specific work), and can be expressed by equation 2.2 (Gülich, 2008:47).

$$Y = \frac{P_{2,tot} - P_{1,tot}}{\rho} = gH \qquad 2.2$$

Where:

$Y = Work$

$P_{1,tot} = Total\ pressure\ at\ point\ 1$

$P_{2,tot} = Total\ pressure\ at\ point\ 1$

$\rho = Fluid\ density$

$H = Head$

$g = Gravitational\ acceleration$

Bernoulli's Equation for incompressible flow defines the total pressure displayed in equation 2.3 (Gülich, 2008:4).

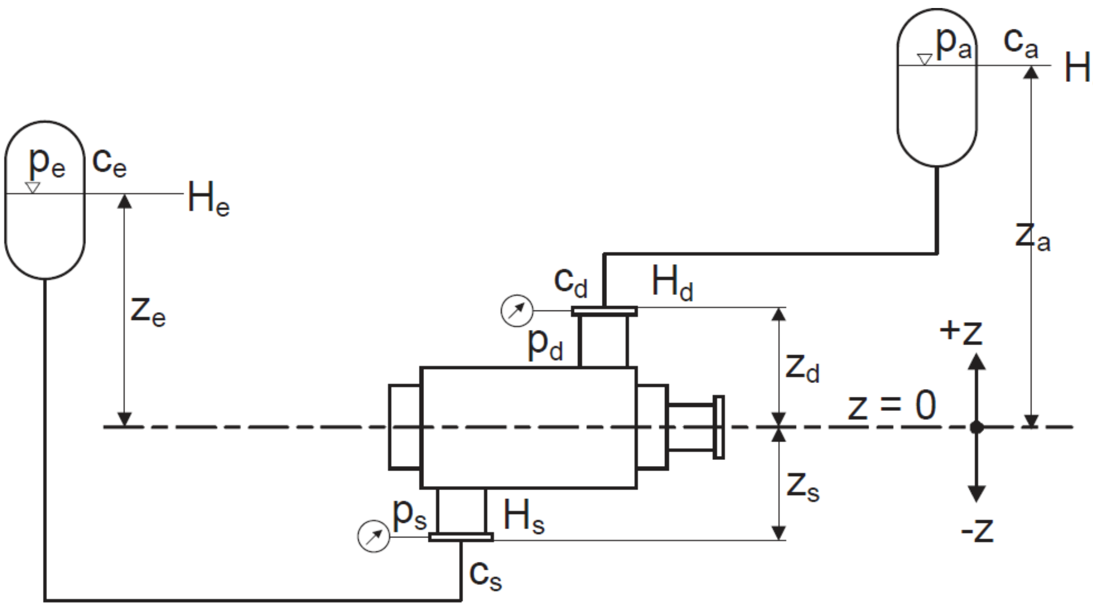
$$p_1 + \frac{\rho}{2}c_1^2 + \rho g z_1 = p_2 + \frac{\rho}{2}c_2^2 + \rho g z_2 + \Delta p_v + \rho \int_{s_1}^{s_2} \frac{\partial c}{\partial t} ds \qquad 2.3$$

According to equation 2.3 the total pressure consists of the stagnation pressure ($\frac{1}{2}\rho x c^2$), the pressure corresponding to the geodetic head (ρ x g x z), and the static (pr system) pressure (p). Referring to Table 2-2, a pump's dynamic head is measured by the difference between the suction and discharge pressure between the suction and discharge nozzles; expressed as heads: $H = H_d - H_s$ (Subscript s= suction nozzle, d= discharge nozzle (Gülich, 2008:48). The Equation for total dynamic head H is displayed as equation 2.4.

$$H = \frac{P_d - P_s}{\rho g} + Z_d - Z_s + \frac{c_d^2 - c_s^2}{2g} \qquad 2.4$$

In equation 2.4 all energies are expressed as "energy heads": the static heads ($\frac{p}{\rho \text{ x } g}$) measurable at the discharge or suction nozzle, the velocity heads ($\frac{c^2}{2g}$) and the potential energy (z). Specific work and head are independent of the medium's type or density. Thus a pump theoretically produces the same head when transporting air, mercury or water. But it does not create the same rise in pressure that a manometer could measure. All stresses, forces, powers and pressure differences are proportional to the density (Gülich, 2008:48). Table 2-2 shows that measurement or calculations must consider the different components that make up the head.

Table 2-2: The different components that make up the head

Description	Equation	Eq.
Head at inlet	$H_s = \frac{P_s}{\rho g} + z_s + \frac{c_s^2}{2g} = H_e - H_{v,s}$	2.4.1
Head at outlet	$H_d = \frac{P_d}{\rho g} + z_d + \frac{c_d^2}{2g} = H_a - H_{v,d}$	2.4.2
Total dynamic head	$H_{tot} = H_d - H_s$	2.4.3
	$H_{tot} = \frac{P_d - P_s}{\rho g} + Z_d - Z_s + \frac{c_d^2 - c_s^2}{2g}$	2.4.4
		

(Gülich, 2008:49)

2.3.3 Flow

The two parameters required to determine the size of a pump are the total head and the capacity. The capacity is the volumetric flowrate and is usually expressed in cubic meters per hour (m^3/h), cubic meters per second (m^3/s) or in litres per second (l/s). The requirements of a system where a pump is located determine the required capacity (Volk, 2013:3). A pump must deliver the required head to ensure the required volumetric flow rate through the given pumping system (Gülich, 2008:48). A pumping system is designed for a specific throughput, like a vessel that must be emptied or filled in a particular time frame. Regardless of the design of a pumping system, achieving the designed flow rate for the pump is usually possible (Volk, 2013:3). The design value of the flow rate (Q_{design}) is usually specified for the demand of the flowrate. An individual pumping system's design value of demand flow rate is specified, for example, by the expected water withdrawal from a water supply system. The required head (H_{design}) is usually determined to correspond with the design flow rate (Q_{design}). The required head is determined mostly by calculation on the basis of assumed or known hydraulic loss, or the resistance coefficient of the hydraulic installation's individual components. However, the majority of pumping systems are not permanently operated at their design condition. The flow rate demand (Q_{demand}) varies during the pumping system's running time, within a range displayed in equation 2.5.

$$Q_{demand,min} \leq Q_{demand} \leq Q_{demand,max} \qquad 2.5$$

Depending on the application, the flow rate range described in equation 2.5 can be pretty broad or small. Applications with a relatively small demand flow rate range can be categorised as a nearly constant flow system. Applications with a pretty broad demand flow rate range can be classified as a widely variable flow system. The maximum demand flow rate ($Q_{demand,max}$) is usually slightly greater than or equal to the design flow rate (Stoffel, 2015:7).

2.3.4 Power

A pump's useful power Pu can be calculated by multiplying the transported mass flow ($m = \rho \text{ x } Q$) by specific work (Y), which represents energy transferred per unit mass (Gülich, 2008:50). The equation 2.6 for specific work becomes:

$$P_u = \rho YQ = \rho gHQ = Q\Delta p \qquad 2.6$$

The power required at the pump coupling is more than the useful power because of all the pump losses (Gülich, 2008:50). Losses in a machine arise whenever a fluid flows through it. The useful power displayed in Equation 2.6 is always smaller than the supplied power P at the pump shaft. The sum of all losses ($\sum P_v = P - P_u$) is dissipated into heat. A pump experiences additional losses ("secondary losses") along with hydraulic losses so that altogether the following sources of loss must be taken into account (Gülich, 2008:93):

1. Mechanical losses (P_m) in the shaft seals and bearings. These losses do not generally result in the heating of the fluid and are thus considered external losses.

2. Leakages caused by impeller leaks are defined as volumetric losses, which include:

(a) Q_{sp} – The leakage occurring through the annular seal at the pump's impeller

(b) Q_E – The leakage occurring through the axial thrust balancing device

(c) Q_h – The leakage occurs in special cases where the fluid is circulated within a pump to branch off the fluid used for auxiliary purposes (flushing, cooling, hydrostatic bearings or sealing)

As mentioned above, all flows must be considered when calculating pump performance and volumetric efficiency. The power (P_L) required to pump all the leakages becomes: $P_L = \frac{(Q_{sp}+Q_E+Q_h)\rho g H}{\eta_h}$, where η_h is the volumetric efficiency.

3. Disk friction losses (P_{RR}) are generated on the front and rear shrouds of the impeller, which rotate in the fluid as hydraulically rough or smooth disks.

4. The components of axial thrust balance devices create a similar friction loss (P_{er})

5. Throttling losses (P_{s3}) occurs in the "interstage seal" in multistage pumps.

6. Hydraulic losses caused by turbulent dissipation and friction in all the components between the discharge and suction nozzle are covered by hydraulic efficiency. The dissipated power is $P_{vh} = \rho g H Q \left(\frac{1}{1-\eta_h}\right)$

7. High losses (P_{Rec}) are created by fluid circulation at part load due to a momentum exchange between non-separated and stalled fluid zones. These losses are zero near the best efficiency point if a pump is designed correctly. When operating at a low flow rate or against a closed valve, these losses make up the greatest part of the energy losses.

The secondary losses making up the power balance in a pump are displayed in Figure 2-12.

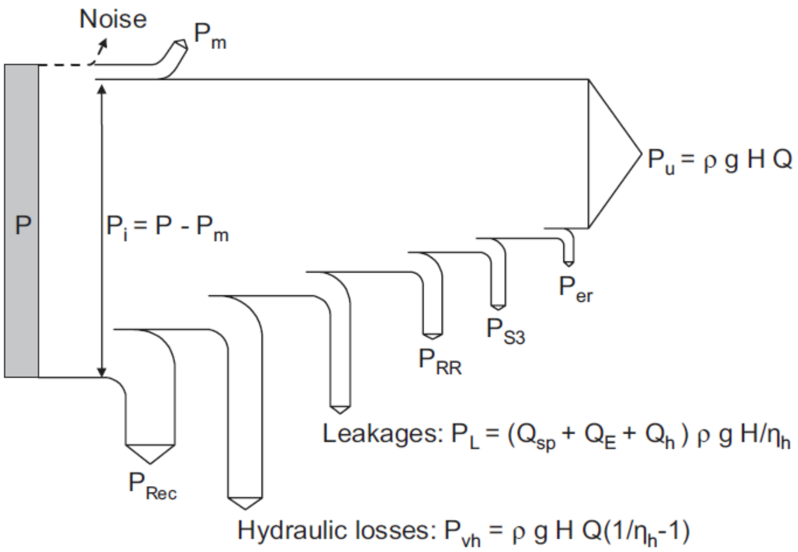


Figure 2-12: Power balance in a pump

(Gülich, 2008:94)

The demanded values of head and flow rate determine the hydraulic power demand, which is determined by the flow rate demand (Q_{demand}) and the corresponding pump head (H_{demand}) as described in equation 2.7, where the fluid density is defined by ρ, and the gravitational constant is described by $g = 9.81\ m/s^2$.

$$P_{hyd,demand} = \rho . g . Q_{demand} . H_{demand} \qquad 2.7$$

By inserting the maximum flow ($Q_{100\%}$) and head ($H_{100\%}$) demand into equation 2.7, the maximum hydraulic power demand can be calculated as displayed in equation 2.8.

$$P_{hyd,100\%} = \rho . g . Q_{100\%} . H_{100\%} \qquad 2.8$$

The values for $P_{hyd,100\%}$, $H_{100\%}$, and $Q_{100\%}$ are usually taken as the basis for the pumping system's design, including the selection and specification of the pumping unit (Stoffel, 2015:10).

2.3.5 Pump unit efficiency

The primary purpose of a pump unit is to convert electrical energy into fluid energy, where the electrical energy is the input, and the fluid energy is the output. The conversion of electrical energy to fluid energy is affected in two steps.

In the electric drive of the pump unit, which consists of an electric motor, the electric energy is converted to mechanical energy and transmitted to the pump by a rotating shaft. An electric drive's efficiency is the ratio between the electrical input power (P_1) and the mechanical output power (P_{mech}), as displayed in equation 2.9 (Stoffel, 2015:10).

$$\eta_{drive} = \frac{P_{mech}}{P_1} \qquad 2.9$$

Where the mechanical power output (P_{mech}) is the product of the shaft torque (T) and the angular velocity (ω), as displayed in equation 2.10 (Stoffel, 2015:10).

$$P_{mech} = \omega . T \qquad 2.10$$

Electric motors are usually selected and classified according to their nominal efficiency. The nominal efficiency point is the motor's efficiency at the rated operating condition – shaft rotational speed and mechanical power. A pump converts the input rotational mechanical energy (P_{mech}) into the output hydraulic energy (P_{hyd}). A pump's efficiency (η_{pump}) is the ratio between mechanical and hydraulic power, as displayed in equation 2.11 (Stoffel, 2015:11).

$$\eta_{pump} = \frac{P_{hyd}}{P_{mech}} \qquad 2.11$$

Where the pump's usable output power (P_{hyd}) is described in equation 2.12.

$$P_{hyd} = \rho . g . Q_{pump} . H_{pump} \qquad 2.12$$

In equation 2.12, (H_{pump}) is the actual head delivered by the pump, and (Q_{pump}) is the actual flow rate delivered by the pump. The pump efficiency is strongly dependent on the flow rate (Q_{pump}) delivered at a constant speed (n). The pump efficiency shows a distinct maximum at the best efficiency point (BEP) and the corresponding pump flow rate (Q_{BEP}). The complete pump unit's efficiency is described in equation 2.13 by combining the two energy conversion steps in a pump unit (Stoffel, 2015:11).

$$\eta_{unit} = \eta_{pump}.\eta_{drive} = \frac{P_{hyd}}{P_1} = \frac{\rho.g.Q_{pump}.H_{pump}}{P_1} \qquad 2.13$$

By combining equations 2.11 and 2.12, the pump efficiency can be determined by equation 2.14 (Stoffel, 2015:11).

$$\eta_{pump} = \frac{\rho.g.Q.H}{P_{mech}} \qquad 2.14$$

The mechanical power(P_{mech}) supplied to the pump is described by equation 2.15, as derived from equation 2.9.

$$P_{mech} = P_{motor}\ .\eta_{motor} \qquad 2.15$$

By combining equations 2.14 and 2.15 the pump efficiency can be calculated with equation 2.16 (Yates & Weybourne, 2001:104).

$$\eta_{pump} = \frac{\rho.g.Q.H}{P_{motor}.\ \eta_{motor}} \qquad 2.16$$

Pump efficiency is also expressed in terms of specific power consumption (P_s), which is expressed by equation 2.17 (Yates & Weybourne, 2001:105).

$$P_s = \frac{P}{Q} = \frac{\rho.g.Q.H}{\eta_{pump}} \qquad 2.17$$

Equation 2.17 is often expressed in more familiar units such as kWh/Ml, which can be determined by equation 2.18 (Yates & Weybourne, 2001:105).

$$P_s = \frac{P_{motor}(kW).1000}{Q(m^3/s).3600} \quad 2.18$$

This is a useful indicator when comparing a system's performance before and after improvements were made (e.g. pump refurbishment). Expensive systems where there is a significant potential for cost savings through power consumption reductions can be identified if the power consumption and total flow are metered on-site (Yates & Weybourne, 2001:105).

2.3.6 Motor efficiency

Electric motors consume approximately 35-40% of the electrical energy generated worldwide in industrial applications. Around 70% of industrial electricity is consumed by electric motors, making it the most important load type by far. Examples of industrial applications are fans, conveyor belts, pumps, presses, crushers, mills, packaging equipment, centrifugal machines, grinders, elevators and others. Electric motors are particularly attractive for efficiency improvements due to their wide use (De Almeida *et al.*, 2013:1).

The energy efficiency of a pumping system is partially affected by the efficiency of the electric motor (Ahonen *et al.*, 2014:1). The electric motor chosen for a pumping system should be reliable. There are common motor types used in pumping applications. The following sections will describe the energy loss and efficiency evaluation of the following motor types: permanent magnet synchronous motor, squirrel cage induction motor, switched reluctance motor, and a synchronous reluctance motor (Shankar *et al.*, 2016:500). The internal losses occurring in an electrical motor can be broadly classified as core losses, copper losses, frictional losses, stray load losses and windage losses (De Almeida *et al.*, 2010:14). Normally higher efficiency class permanent magnet synchronous motors and synchronous reluctance motors exhibit higher performance characteristics when operating at lower and fractional operating speeds. The windings and lamination type play a significant role in determining a motor's efficiency. Irrespective of all the motor's parameters, the motor's performance is dominated by the laminations. The international efficiency class (IEC) of induction motors are defined by the IEC60034-30-1 standard. The induction motors are classified as IE class-1 (Standard efficiency), IE class-2 (high efficiency), IE class-3 (premium efficiency) and IE class-4 (super premium efficiency) (Shankar *et al.*, 2016:500). An IE class-5 (ultra-premium efficiency) is currently being considered in addition to the IE class-4. IE1, IE2, IE3, IE4, and IE5 Classes are shown in Figure 2-13 for 4-pole, 50/60-Hz motors as classified in the 2nd Edition of IEC60034-30 (De Almeida *et al.*, 2013:1).

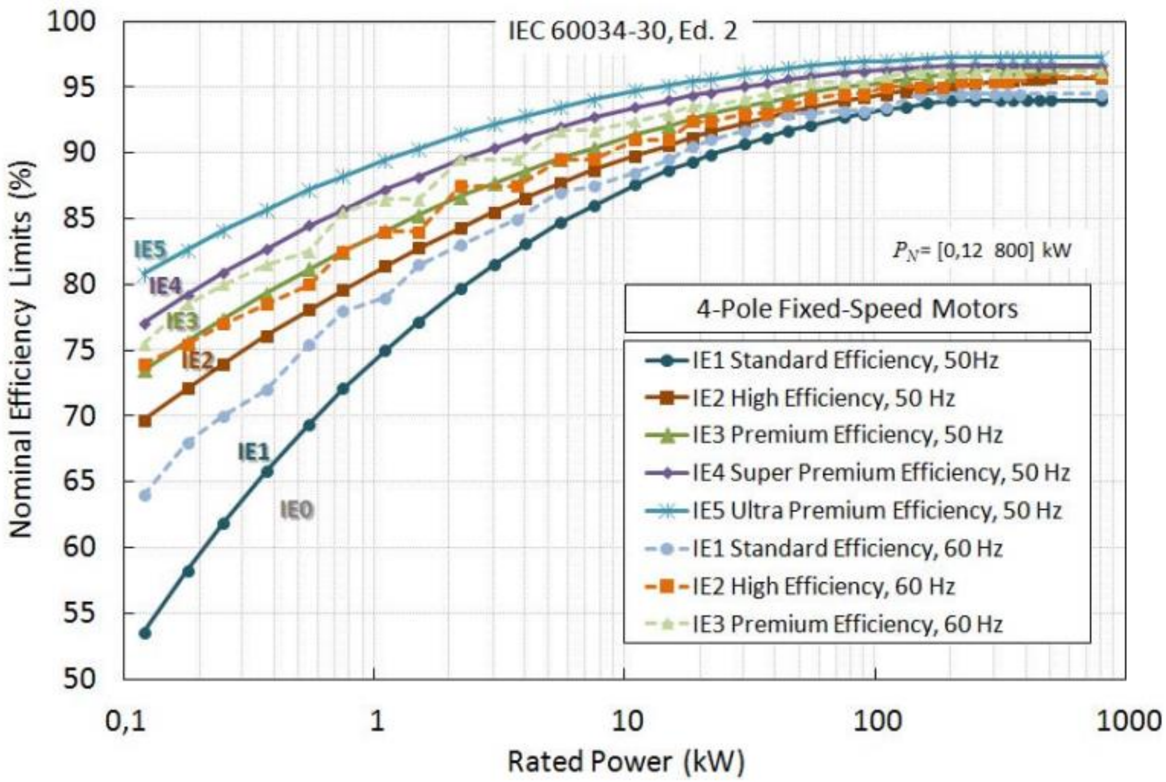


Figure 2-13: IE Motor class efficiency curve

(De Almeida *et al.*, 2013:1)

While many types of electric motors are available on the market, three-phase, squirrel-cage induction motors (SCIMs) are the most prevalent (De Almeida *et al.*, 2013:1). Figure 2-14 shows an overview of the different types of electrical motors.

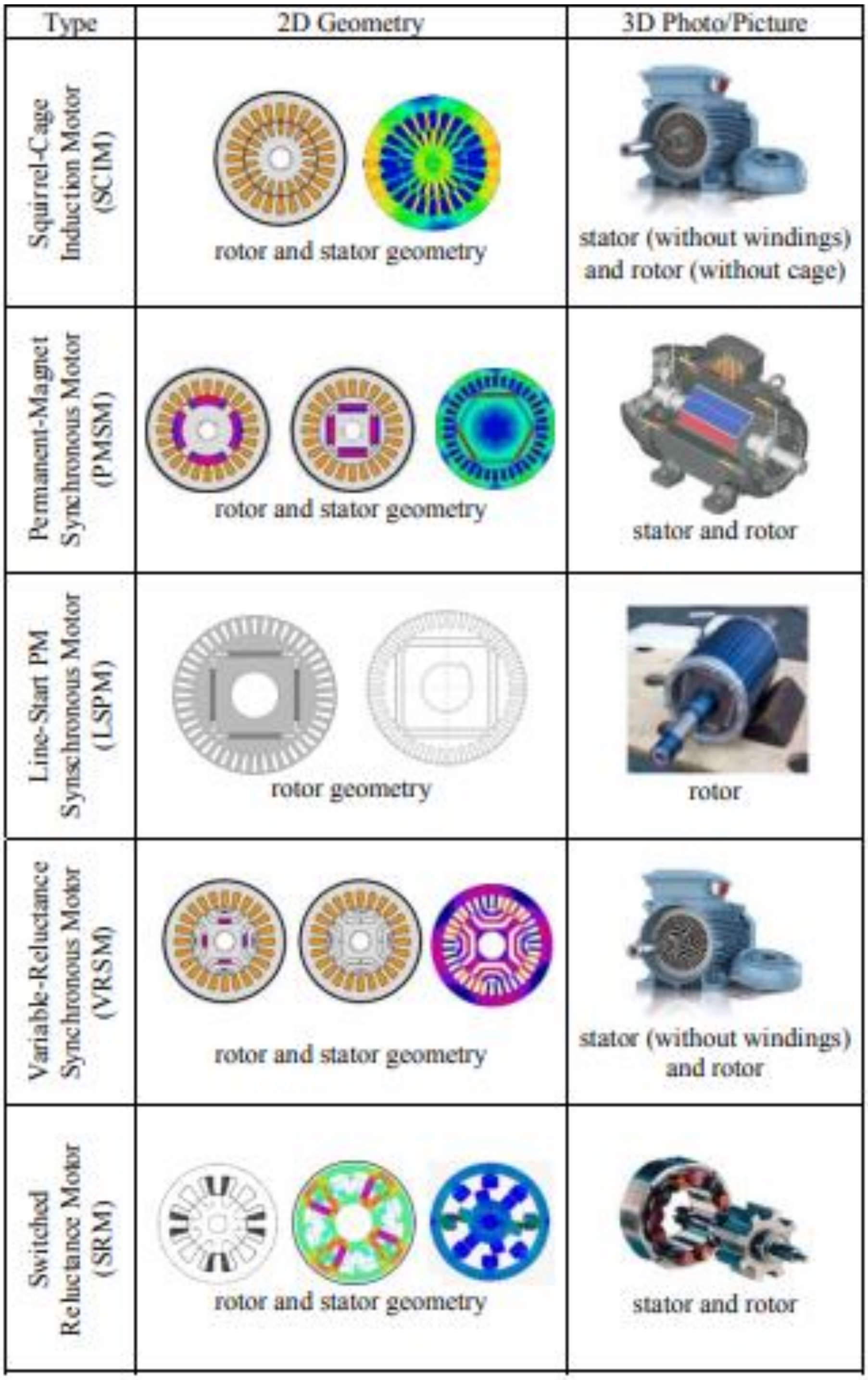


Figure 2-14: Overview of the different electrical motors

(De Almeida *et al.*, 2013:3)

2.4 Pump characteristic curves

A pump's head, power usage, and efficiency all change when the flow rate changes. Plotting these parameters against the volume flow rate on a pump curve, the pump characteristics are obtained (Gülich, 2008:51). A simple representation of a pump curve is shown in Figure 2-15.

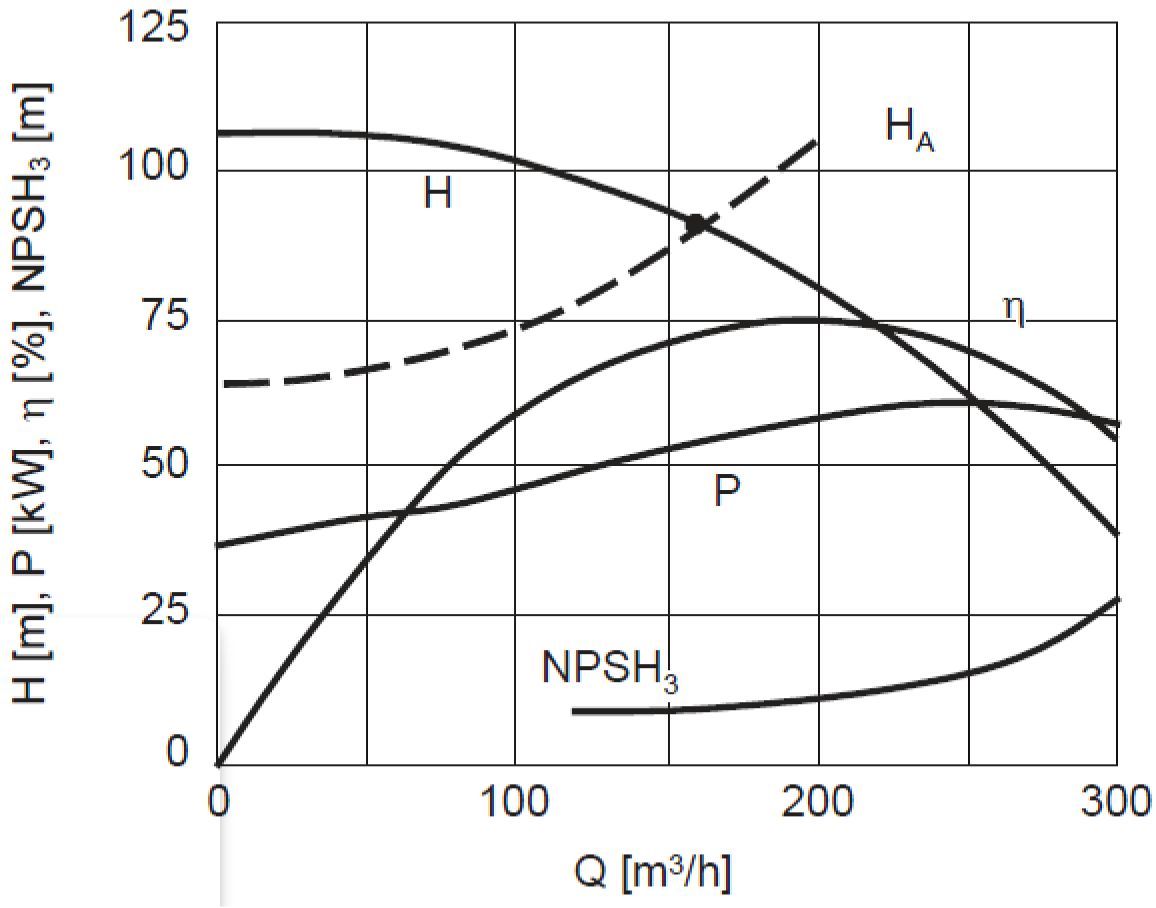


Figure 2-15: Pump and systems characteristics curve

(Gülich, 2008:51)

The pump characteristic curves indicate the pump's behaviour under changing operating conditions as shown in Figure 2-16. The power (P). head (H), and efficiency (η) are plotted against the flow rate (Q) at a constant speed (n) as shown in Figure 2-17 (Sulzer, 2010:27)

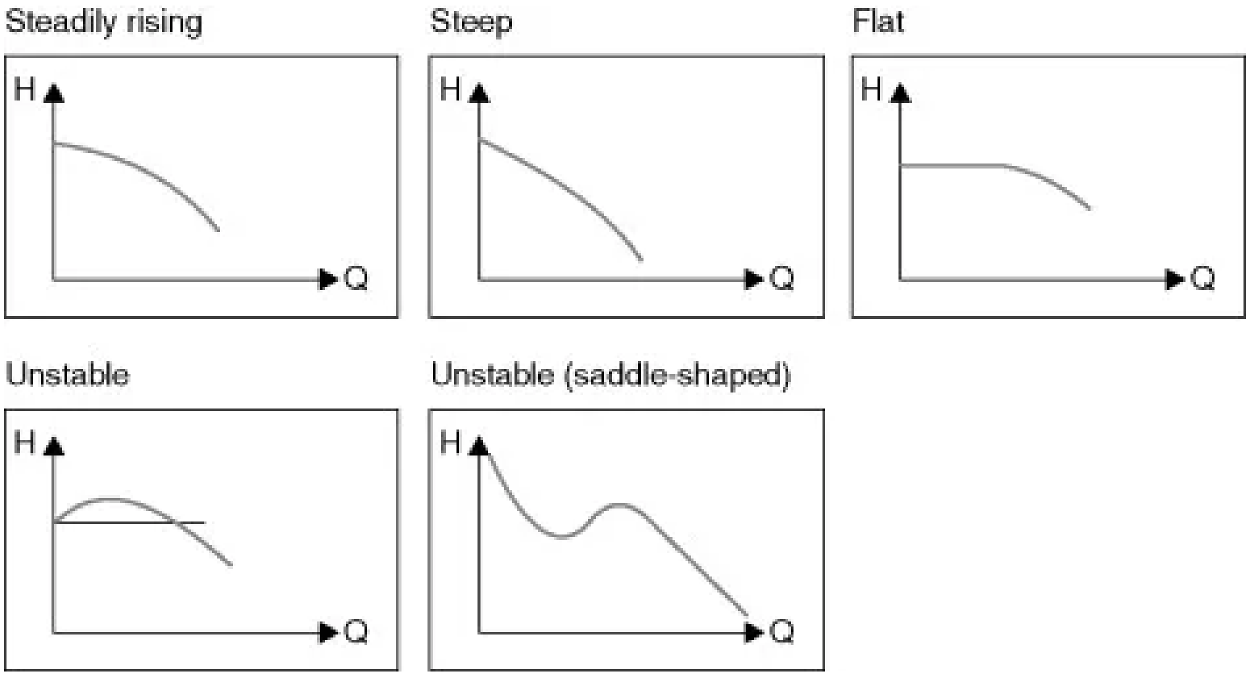


Figure 2-16: Typical shapes of pump characteristic curves

(Sulzer, 2010:28)

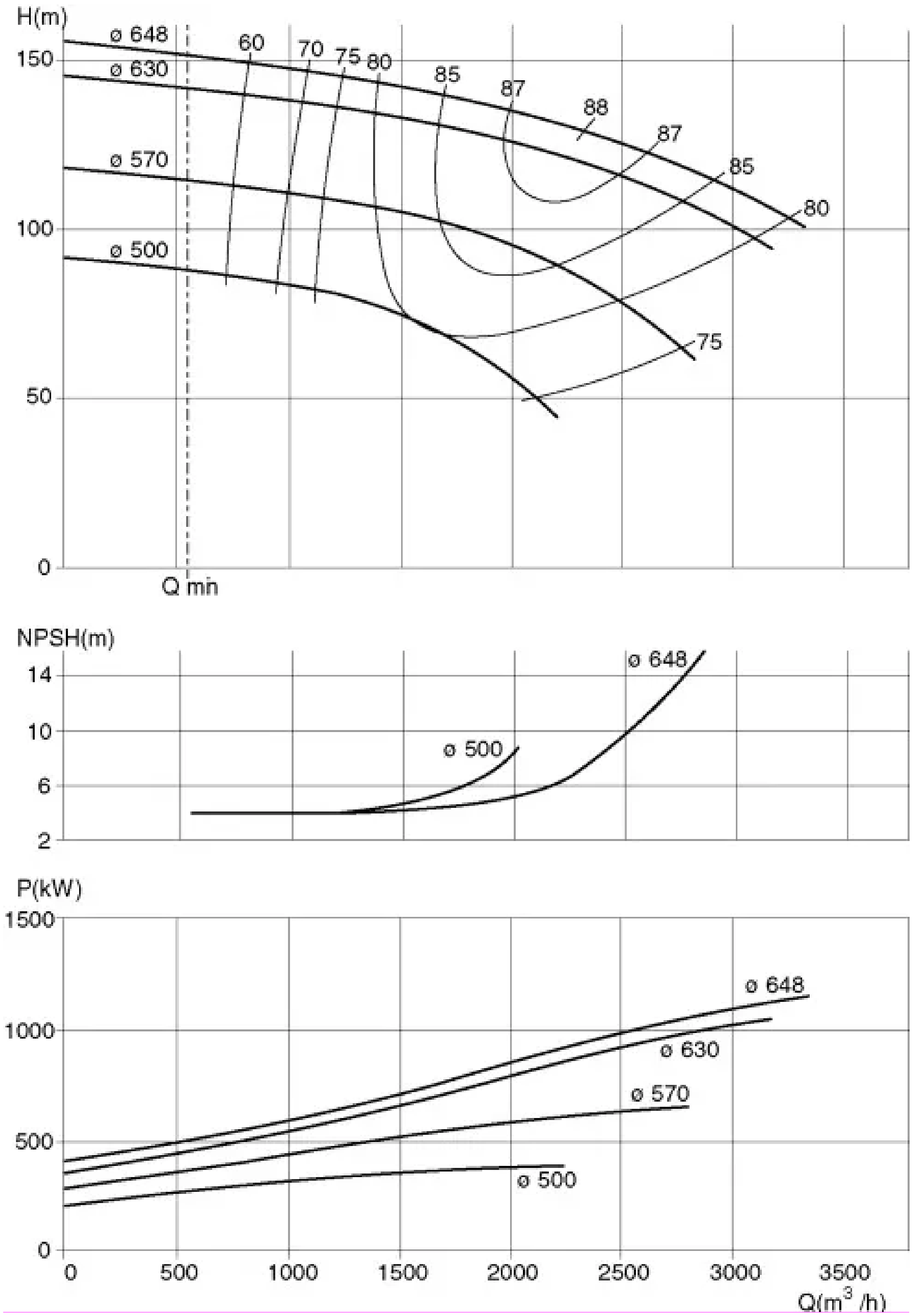


Figure 2-17: Typical pump characteristics with constant speed and various impeller diameters

2.5 Pump performance analysis

2.5.1 Overview

A field test consists of taking measurements of a pump's total head, flow, and power consumption during operation. The field test data and the motor efficiency can be used to calculate the pump's efficiency. Measuring the flow accurately of an installed pump can be particularly difficult without expensive flow-measuring equipment. When the flow, total head, and motor power (including the motor's known efficiency), the result's accuracy is equal to the square root of the sum of the squares of the individual components' accuracies (Volk, 2013:166). equation 2.19 expresses the resulting accuracy.

$$\%_E = \sqrt{\%_Q^2 + \%_H^2 + \%_P^2} \qquad 2.19$$

Where the accuracy of the pump efficiency is expressed by $\%_E$, the accuracy of the flow measurement is expressed by $\%_Q$, the accuracy of the total head is expressed by $\%_H$, and the accuracy of the power measurement is expressed by $\%_P$ (Volk, 2013:166). According to equation 2.19; the accuracy of efficiency testing is less precise than the accuracy of the least accurate variable measured. In most cases, the flow measurement is the least precise measurement. Very little benefit would be gained by modifying the test assembly to allow more accurate motor kilowatt or total pump head measurement. Even though pump field testing has shortcomings, it does have several significant benefits. The primary benefit of pump field testing is benchmarking of flow, power, and total head or efficiency at the point or points of operation on the pump curve when the pump is newly installed. The benchmark data can be compared to pump performance in subsequent periodic pump field tests. These tests can bring attention to developing problems before significant deterioration occurs. Early detection of these problems permits better maintenance planning to restore a pump to its original operating condition after the damage is caused by degradation (Volk, 2013:167).

2.5.2 Measuring flow

Flow measurement is the first component of pump field testing. There are various methods to measure pump flow. The different measurement methods vary in complexity, cost and measurement accuracy. Many methods are only designed for certain types of fluids or for a specific range of flows. Most of the flow measurement equipment is fixed in a piping system, whereas some types are portable. Most of the measuring devices cause a pressure drop when the liquid flows through them. As a result of being exposed to the pumped liquid, many flowmeter types lose accuracy over time due to the effects of erosion and/or corrosion (Volk, 2013:167).

2.5.3 Measuring total head

Pressure gauges (or vacuum gauges when there is a vacuum in the suction) are the most common method of measuring the total head (Volk, 2013:171). Figure 2-18 displays a typical pressure gauge setup of a pump field test.

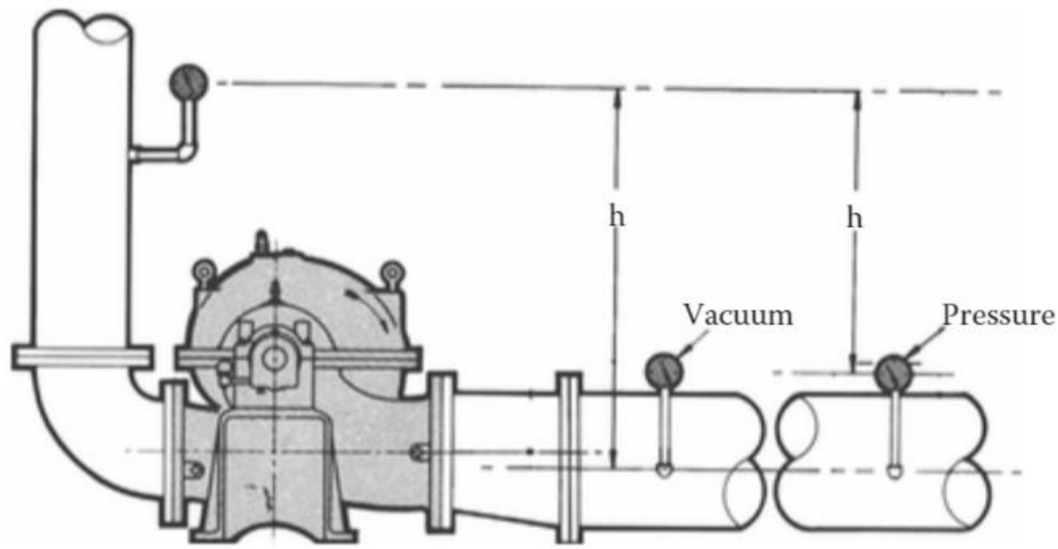


Figure 2-18: A typical pressure gauge setup of a pump field test

(Volk, 2013:171)

When there is a vacuum in the suction, the formula for the total head (H_{Total}) is displayed in equation 2.20

$$H_{Total} = discharge\ gauge\ reading\ (m) + vacuum\ gauge\ reading\ (m) + distance\ between\ point\ of\ attachment\ of\ vacuum\ gauge\ and\ centerline\ of\ dischargauge, h(m) + \left(\frac{V_d^2}{2g} - \frac{V_s^2}{2g}\right) \qquad 2.20$$

A pressure gauge is used on a pump suction line when there is positive pressure in the suction line, then the formula for the total head (H_{Total}) is displayed in equation 2.21.

$$H_{Total} = discharge\ gauge\ reading\ (m) - suction\ gauge\ reading\ (m) + distance\ between\ centerlines\ of\ dischargauge\ and\ suction\ gauges, h(m) + \left(\frac{V_d^2}{2g} - \frac{V_s^2}{2g}\right) \qquad 2.21$$

If the discharge pressure gauge is higher than the suction pressure gauge, the third term in both formulae is positive. The term is negative if the discharge pressure gauge is lower than the suction pressure gauge (Volk, 2013:171). These two gauges are usually ignored since the gauges are often so close in elevation. The last term in the equations is the change in velocity head due to the difference in the discharge and suction line diameter at the gauge location. The flow is measured or estimated to calculate the $\left(\frac{V_d^2}{2g} - \frac{V_s^2}{2g}\right)$ at the suction and discharge pressure gauges, or it can be looked up in friction tables. Often, the velocity head difference is so insignificant compared to the total pump head that it can be safely ignored. The pump head can also be measured with differential pressure transmitters, which convert the differential pressure in kPa to a 4 to 20-milliampere (mA) signal. Pressure transmitters are more expensive than gauges but are more accurate and can be used to monitor the pump head continuously (Volk, 2013:171).

2.5.4 Measuring power consumption

The power input required by a motor driving a pump can be measured with two methods. The first is using a kilowatt transducer if one is available. The second method is to obtain the input kilowatts (kW) by measuring the ampers and volts using an ammeter and voltmeter. For three-phase power, the average amperage between the three legs is used (Volk, 2013:173). The formula in equation 2.22 is used to calculate the input kW.

$$kW_{in} = \frac{\sqrt{3}.voltage.ampere.power\ factor}{1000} \qquad 2.22$$

The constant $\sqrt{3}$ is used for three-phase power measurement but becomes 1.0 for single-phase power measurement. The power factor varies with the motor load and can be obtained from the motor manufacturer (Volk, 2013:173). Electrical power can also be measured with power meters. The basic concept of a power meter is that it measures the voltage and current. The power is calculated by the power meter by using the measured parameters as variables (Volk, 2013:174).

2.6 Pump degradation

2.6.1 Overview

Pump efficiency degradation is caused by pump wear. The amount of internal wear that a pump can tolerate depends on the kind of pump and the system characteristics it operates in. Although slurry pumps are built to handle corrosive liquids, wear is accelerated by rapid velocities, big particles, and high concentrations. There are many types of wear that can occur inside a pump like wear on impeller outer ends, internal component wear, nodular growths, cavitation, blockage, casing corrosion, impact damage, leaking external seals and maintenance errors (Beebe & Beebe, 2004:24).

2.6.2 Pump wear

Wear on the vane outer ends reduces the impeller diameter. Most frequently, corrosive or abrasive liquids cause wear on the vane's outer ends. All flows have reduced Head and Power curves, which would have the same result if a smaller diameter impeller had been installed in the pump casing. Performance might produce a flow that is insufficient to fulfill production requirements, and in any event, the pump will consume more electrical energy for a given flow. This will be especially noticeable if the second pump of two must be run in parallel because neither pump can provide the necessary flow on its own. Running both pumps at once while one of the pumps is severely worn out may result in a loss of flow from the worn pump, resulting in increased energy consumption. (Beebe & Beebe, 2004:24).

Liquid can circulate from the impeller output to the suction due to wear at the impeller/sealing ring interface (i.e. sealing ring or wear). Degradation in the horizontal joint of split-casing multi-stage pumps also causes internal leakage, which permits some flow to bypass a single stage or multiple stages. Internal leakage has the effect of lowering the output flow for a given head, or the flow leaving the pump to perform useful work. In other words, the total flow through the impellers themselves equals both the output of the pump and any leakage flows that is recycled inside the pump (Beebe & Beebe, 2004:25).

2.6.3 Relationship between pump efficiency and internal wear

With pumps of lower Specific Speed, the relative additional power required with increased internal wear is greater. Figure 2-19 uses data from the Hydraulics Institute graph to show the effect of internal wear on power consumption. The bottom curve shows the increase in power consumption when the wear ring clearances are 150% of the design clearance. The top curve shows the increase in power consumption when the wear ring clearances are 200% of the design clearance. It should be noted that pumps with high specific speeds exhibit a much smaller relative increase, but the energy increase may still be substantial due to the size of these pumps (Beebe & Beebe, 2004:28).

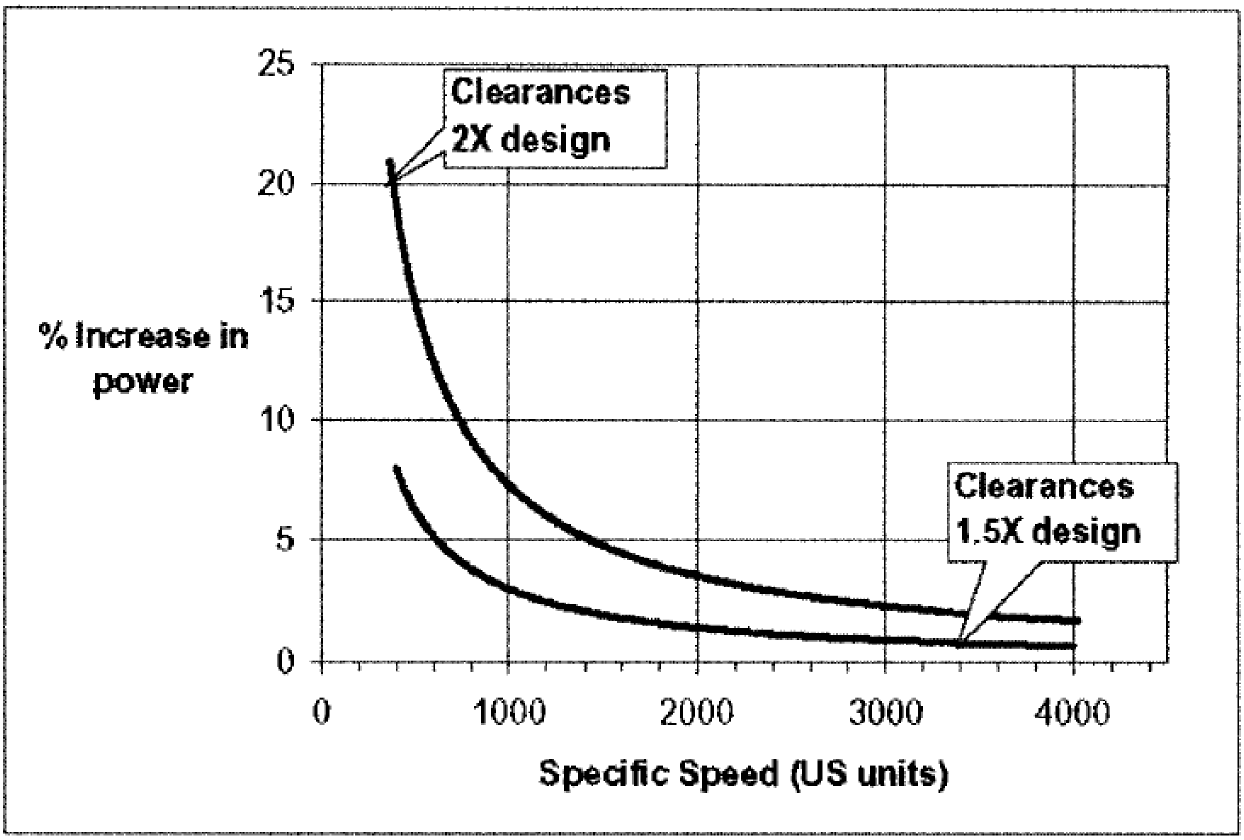


Figure 2-19: Effect of internal wear on pump efficiency (and power consumption)

(Beebe & Beebe, 2004:28)

2.6.4 Rate of wear

The main factor influencing wear in a pump is velocity, and the wear rate is typically exponentially proportional to local velocities. The wear in the casing is determined by the head requirement, which is directly related to the impeller's tip velocity. A pump's wear rate varies depending on the liquid it pumps and the materials used to fabricate the pump. After testing more than 300 medium to large split casing pumps, the water industry discovered an average 8% decline in efficiency over a ten-year period. The typical cast iron casings, gunmetal or bronze impellers, leaded bronze bushes and wear rings were present on the tested pumps. (Beebe & Beebe, 2004:29). There has been a significant amount of research on developing techniques to evaluate pump performance. However, the literature rarely discusses pump wear rates and pump performance lifetime (Eaton *et al.*, 2018:5). The rate of pump degradation and the magnitude thereof depends on the installation, the duty and the pump design as represented in Figure 2-20 (Yates & Weybourne, 2001:102).

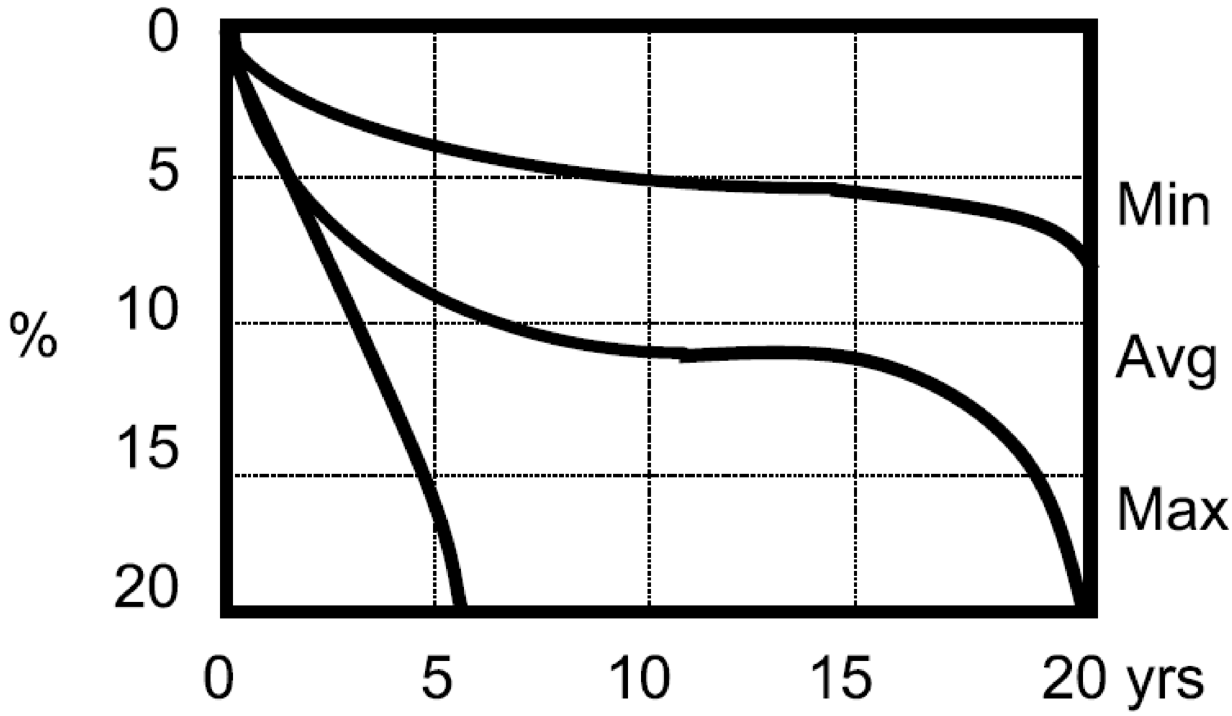


Figure 2-20: Pump degradation with age

(Yates & Weybourne, 2001:102)

2.7 Pump refurbishment

A multistage centrifugal pump has a 15-year expected lifespan. If the necessary maintenance is carried out, the normal life of a pump can be extended by up to 15%. This can reduce the amount of electrical energy used by up to 7%. When the pump is used outside of its intended conditions, its lifespan decreases. If the fluid being transferred has corrosive properties, maintenance frequency should be increased. If the cost of refurbishing a pump exceeds 40% of the cost of a new pump, it is not financially feasible. Renovating or modernizing a pump typically entails interior work, updating the seal system, and redesigning the lubrication oil system. Improvements to the pump system include modifying the control valve, re-wheeling the pump, and making various piping modifications. If the power consumption rises while the discharge flow remains constant, a pump should be considered for refurbishment. A decreasing efficiency is indicated by increased power consumption. Lower efficiency means that the pump will need to run for longer to move the same amount of fluid. Performance monitoring and condition monitoring of a pump can indicate when a pump should be refurbished (Oberholzer, 2015:16).

2.8 Condition monitoring and performance monitoring analysis

On-line or off-line condition monitoring is a type of maintenance inspection where operational equipment is monitored and the data collected is analyzed to highlight signs of deterioration, identify the root cause of faults, and forecast how long it can be operated safely or profitably. Regular readings are taken at the appropriate times. Monthly vibration monitoring is typical. Quarterly or even yearly monitoring is typical for other purposes. For critical machinery, continuous monitoring may be appropriate. The frequency of readings is frequently increased to facilitate forecasting of the time until the parameter correlates. with the condition where maintenance intervention is necessary when deterioration eventually occurs and the parameter moves outside the repeatability band (Beebe & Beebe, 2004:6). The basic principle of condition monitoring is illustrated in Figure 2-21.

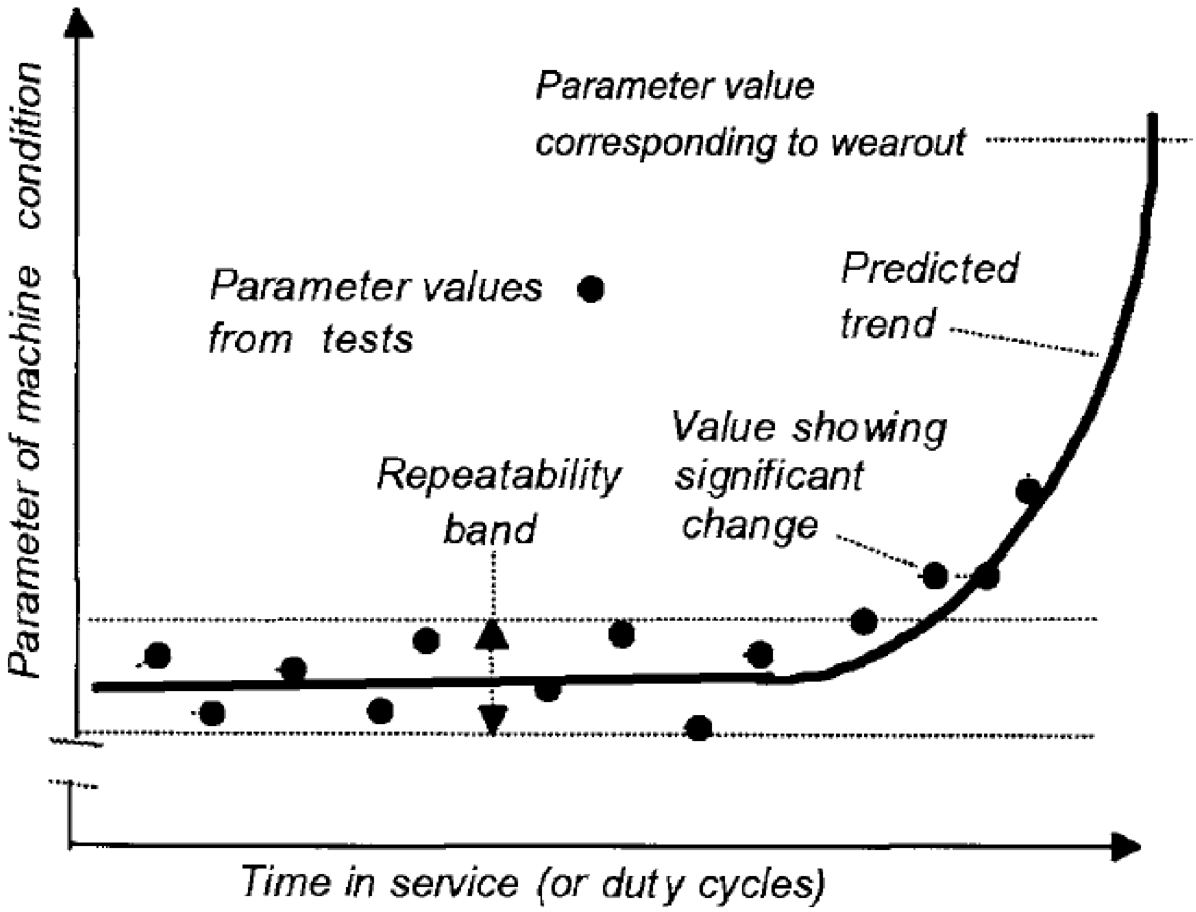


Figure 2-21: The basic principle of condition monitoring

(Beebe & Beebe, 2004:7)

Good quality data, such as that obtained by carefully executed tests, is required for condition monitoring. However, once repeatability is established, a plant's permanently installed instrumentation frequently provides a wealth of useful information (Beebe & Beebe, 2004:7). Performance monitoring is less well known, but it makes it possible to determine the best time to restore performance when a machine's condition deteriorates; resulting in higher energy consumption. Each type of machine or plant component has its own application and set of parameters, which typically call for measurements of quantities like displacement, speed, pressure, temperature and flow. If the repeatability of the monitoring parameters is demonstrated to be sufficiently narrow, permanently installed plant instrumentation may occasionally be used to monitor equipment performance (Beebe & Beebe, 2004:9).

Pump monitoring is divided into two groups, namely condition monitoring and performance monitoring. The efficiency of a pump with the deliverable is determined with performance monitoring. The risk of pump failure is monitored with condition monitoring. Condition monitoring is not replaced by performance monitoring, It assists with the condition monitoring data analysis (Oberholzer, 2015:21). Figure 2-22 shows the benefits and differences between condition monitoring and performance monitoring.

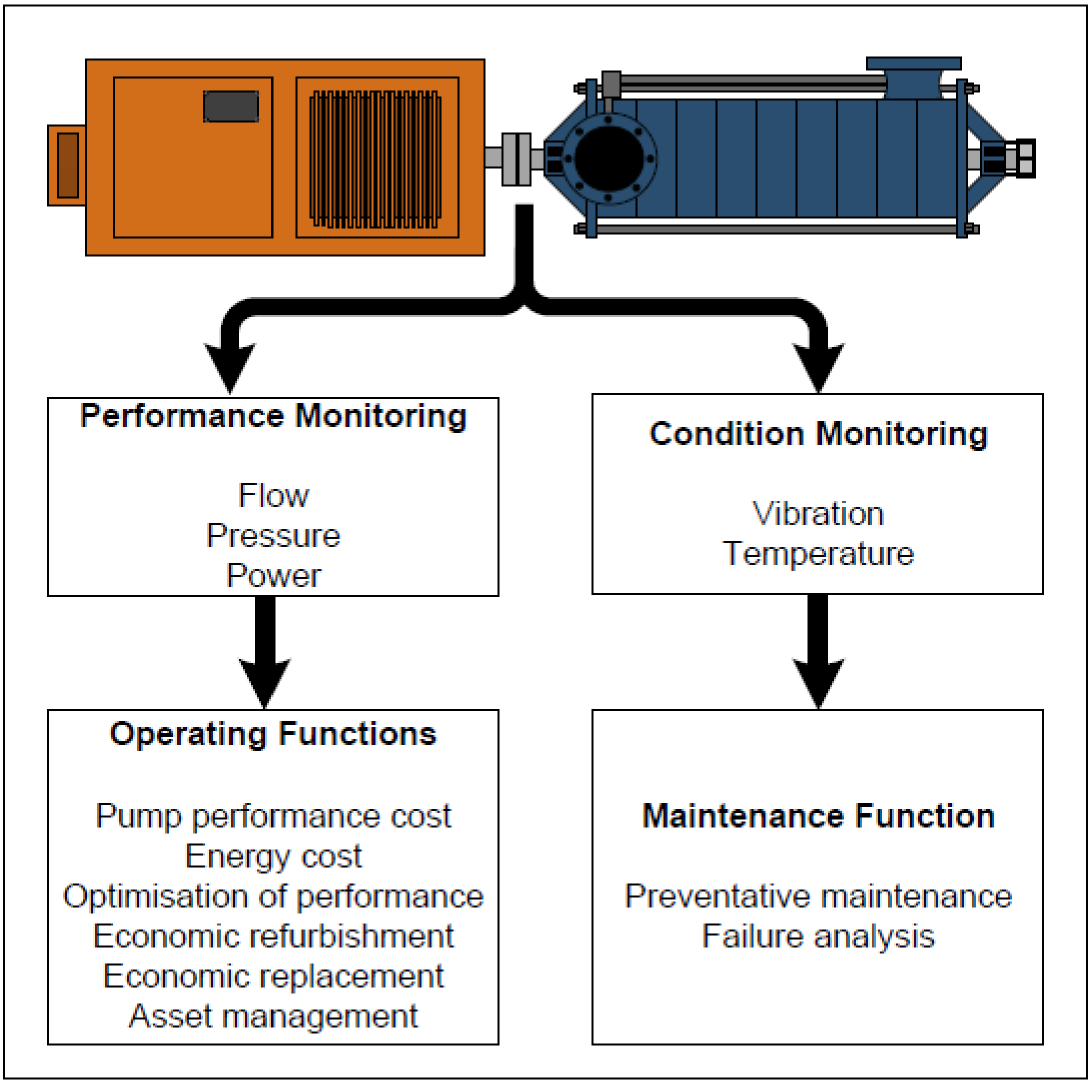


Figure 2-22: Pump performance and condition monitoring

(Oberholzer, 2015:21)

2.9 Predicting energy losses

Various authors have proposed energy efficiency strategies for pumping systems, including maintenance and online monitoring, assessment and reporting, and design and calibration (Torregrossa *et al.*, 2017:1431). The availability of SCADA systems theoretically allows for an increased frequency of energy analysis. The amount of information available on energy performance has significantly increased in recent years as a result of the explosive growth in the popularity of smart energy monitoring systems. The increase of smart energy monitoring systems has increased the popularity of data-driven methods for calculating energy performance models (Qaisar & Zhao, 2022:2). The analysis will be done on the energy efficiency of the pump station as a result of online monitoring equipment available within the selected pump station. All the data captured on the SCADA is accessible for long periods. The availability of smart energy monitoring systems allows for a comprehensive data-driven energy-saving prediction method.

A range of methods used to forecast the outcome of a potential Energy Efficiency Measure (EEM) application is referred to as prediction. The outcomes of the predictions are then utilized to formulate the best energy retrofitting scenarios and to advocate the usage of some EEMs over others. Prediction and recommendation techniques make it possible to respond to a variety of questions, including What is the return on investment for a particular EEM?, Which EEM would perform best in the chosen application, given its characteristics? Which low-cost measures can be used to improve the energy performance of the chosen application? The prediction technique is an adapted bottom-up energy efficiency and saving calculation (Grillone *et al.*, 2020:3). A prediction data-driven energy efficiency and saving model will be used to determine the energy losses that occurred in the pump station, as it predicts the possible energy savings if an EEM had been implemented. The predicted EEM is the refurbishment of pumps within the pump station.

Reichl and Kollmann (2011:423): described the main principle of a bottom-up energy efficiency and saving calculation can be described by equation 2.23:

$$Gross\ energy\ savings_t = Baseline\ energy\ consumption_t - actual\ energy\ consumption_t \quad (2.23)$$

Where *t* refers to the period of interest. Therefore an adapted bottom-up energy efficiency and saving calculation to predict possible energy savings by determining energy losses can be described by equation 2.24:

$$Gross\ energy\ losses_t = Baseline\ energy\ consumption_t - predicted\ energy\ consumption_t \tag{2.24}$$

The baseline energy consumption is the amount of energy used if no direct actions had been done to modify the trajectory of energy consumption. Savings are calculated by comparing measured energy consumption before and after the adoption of a retrofit solution, taking into account the pertinent modifications for changes in circumstances, as savings indicate the absence of energy usage and cannot be directly quantified. A model of the consumption prior to the adoption of the measures must be constructed in order to compare the energy use before and after the application of the EEM. The baseline energy model is the name given to this model. The baseline model, which is crucial in determining energy savings, may be characterized as the energy characterisation of the initial scenario (Grillone *et al.*, 2020:2). A baseline energy consumption for the pump station will be determined through a data-driven analysis. The baseline model will be developed to determine the energy consumption of the pump station before the predicted energy consumption as a result of the EEM application. The baseline model will also include the pump and system efficiency parameters.

2.10 Financial factors influencing pumping systems

2.10.1 Electricity overview of South Africa

Supply uncertainties in the South African business environment have significant economic repercussions on the nation's ability to achieve its industrial goals. Given that the industrial sector makes up the majority of South Africa's GDP, the country's industrial decline and slowing economic growth are directly related to declining electricity sustainability. Eskom, South Africa's public electricity provider, is in a difficult situation as a result of the country's declining electricity supply trend and declining reserves. In an effort to lessen the imbalance between electricity consumption and supply, which poses a threat to the electrical grid system, Eskom has taken steps to intensify electricity rationing through load shedding and a range of tariff increases (Ateba *et al.*, 2019:1324). The electrical tariffs have been on a steep increase since 2007. The average electricity price increased by approximately 460% from 2007 to 2020, when not considering inflation. If inflation is taken into account, the average increase is still around 180% (Labuschagne, 2020). The performance of corporate entities and their investments are impacted by the inadequate and unstable electricity supply in South Africa, which results in higher input costs and tense industrial relations. The impact of an inadequate and inconsistent supply of electricity is a serious constraint on the economy (Ateba *et al.*, 2019:1326).

2.10.2 Electricity consumption of deep-level mines

The South African mining industry is a large consumer of electricity; consuming more than 10% of the country's generated electricity (Ratshomo & Nembahe, 2019:36). Gold is an important economic driver in South Africa (Vosloo, 2008:7). The gold mines are the highest consumer of electricity across the mining sector; consuming almost as much as all the other mining sectors combined (Mare *et al.*, 2016:112-117). South African deep-level mines are among the most energy-intensive in the world, due to the fact that these mines are some of the deepest mines globally (Van der Wateren *et al.*, 2018:1). South African platinum and gold mining sectors are responsible for approximately 33% and 47% of the total electricity consumed by the mining industry respectively (Van Rensburg *et al.*, 2011:124).

2.10.3 Electricity tariffs

The typical electrical demand profile is distributed in three segments. The electrical demand increases during a typical weekday between 07:00 and 10:00 in the morning, and again in the evening between 18:00 and 20:00. The maximum electrical demand in the evening is much higher than the demand in the morning, but the morning demand peak lasts longer. Time-of-use pricing tariffs were introduced by Eskom in an effort to persuade customers to use less energy during times of high demand. Increased electricity tariffs during high peak periods and decreased electricity tariffs during low peak periods are the results of the time-of-use pricing structure. Mega Flex time-of-use tariff structure was developed for mining, industrial and urban customers with a Notified Maximum Demand of more than 1MVA. This tariff structure consists of off-peak, standard, and peak pricing periods (Vosloo, 2008:3). The Megaflex pricing periods are displayed in Figure 2-23.

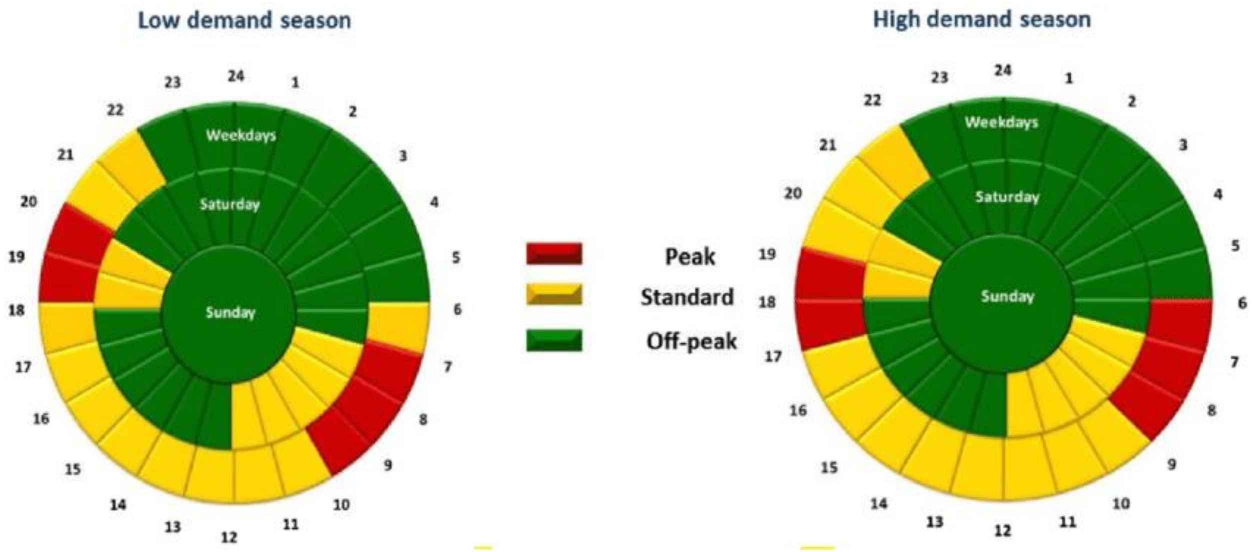


Figure 2-23: Mega Flex tariff variable pricing charts

(Mostafaeipour *et al.*, 2020:2820)

From Figure 2-23 it can be seen that the peak times (red segments) are from 06:00 to 09:00 and 17:00 to 19:00 in the high-demand season, and from 07:00 to 10:00 and 18:00 to 20:00 in the low-demand season. the off-peak times (green segments) are from 22:00 to 06:00 in the high-demand and low-demand seasons. The electricity cost during off-peak times is much cheaper than the peak or standard times. The pricing structure differs significantly between the high-demand season (winter) and low-demand season (summer), as illustrated in Figure 2-24. The reason for the significant price difference is that the electricity demand is much lower in summer (September to May) than in winter (June to August) (Vosloo, 2008:3).

	Rates (c/kWh)	
	High demand season (June to August)	Low demand season (September to May)
Peak	*226.23*	*73.80*
Standard	*75.09*	*55.65*
Off-peak	*41.83*	*36.27*

Figure 2-24: Mega Flex – energy usage tariffs (2014/2015)

(Van Eeden *et al.*, 2014:6)

2.10.4 Demand side management

Eskom launched the DSM (demand side management) program in 1992 to improve response to the variable electricity pricing systems. This program supports initiatives that adapt to the variable pricing structure successfully. Additionally, it involves activities that modify or regulate the user's energy consumption patterns. These activities result in either overall energy consumption reduction or reduced energy consumption during peak time (Vosloo, 2008:5). DSM intervention mechanisms generally fall into one of four categories as shown in Figure 2-25. These mechanisms are load shifting, energy efficiency, strategic load growth and peak clipping.

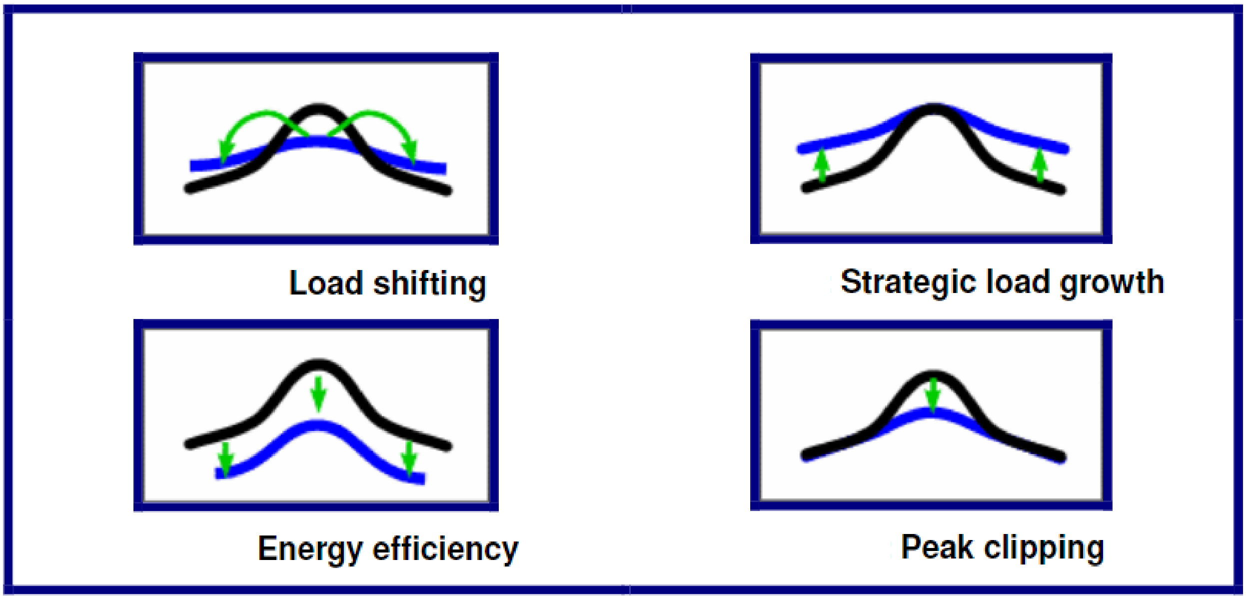


Figure 2-25: The four DSM intervention mechanisms

Readjusting an electricity usage schedule is known as load shifting. Price-based incentives, like time-of-use (TOU) tariffs and real-time pricing (RTP), are used to accomplish this. Utilities with extra power can implement strategic load growth to increase their load strategically. Depending on the time of day, more electricity sales are generated. Conversion to more energy-efficient end-use technologies and procedures is necessary for energy efficiency. Both the customer and the utility benefit from this. Peak clipping enables a utility to briefly turn off the power to a portion of a customer's site. The interruption is made up to the customer (Vosloo, 2008:5).

2.11 Summary

High operating costs are a major concern for South African mines, which can lead to a reduction in mine life (Maregedze *et al.*, 2022:2). The South African mining industry is a large consumer of electricity; consuming more than 10% of the country’s generated electricity (Ratshomo & Nembahe, 2019:36). The gold mines are the highest consumer of electricity across the mining sector; consuming almost as much as all the other mining sectors combined (Mare *et al.*, 2016:112-117).

Due to the high volumes of water collected underground, the mine must be dewatered to continue mining operations. The dewatering process is a necessity for the continuous operation of the mine, and therefore needs to be controlled efficiently. The dewatering process ensures the water levels of the cooling system are maintained and prevents the mine from flooding. The dewatering system uses multiple high-performance pumps to dewater the mine (Groenewald *et al.*, 2013:1-4). The world's largest hydraulic heads are found in South African gold mines. The high hydraulic heads and high volumes to be dewatered place additional strain on deep-level mines, due to the high electricity consumption associated with pumping systems (Winde *et al.*, 2017:679).

Due to the reliability of multi-stage centrifugal pumps, little information is known about performance changes during the pump's operation (Eaton *et al.*, 2018:1). Over the lifetime of the pump, the inefficiencies will decrease and result in increased long-term costs. The performance decrease is usually realised once a significant reduction in performance affects the whole system driven by the pump. The most prominent attribute to the decrease in pump performance; is a pump's degradation over time, yet; no adequate relationship has been developed between the two (Eaton *et al.*, 2018:1).

Pump efficiency degradation is caused by pump wear. The amount of internal wear that a pump can tolerate depends on the kind of pump and the system characteristics it operates in. There are many types of wear that can occur inside a pump like wear on impeller outer ends, internal component wear, nodular growths, cavitation, blockage, casing corrosion, impact damage, leaking external seals and maintenance errors (Beebe & Beebe, 2004:24). . Pumps with high specific speeds exhibit a much smaller relative power increase as a result of internal wear, but the energy increase may still be substantial due to the size of these pumps (Beebe & Beebe, 2004:28).

A multistage centrifugal pump has a 15-year expected lifespan. If the necessary maintenance is carried out, the normal life of a pump can be extended by up to 15%. This can reduce the amount of electrical energy used by up to 7%. If the power consumption rises while the discharge flow remains constant, a pump should be considered for refurbishment. A decreasing efficiency is indicated by increased power consumption. Lower efficiency means that the pump will need to run for longer to move the same amount of fluid. Performance monitoring and condition monitoring of a pump can indicate when a pump should be refurbished (Oberholzer, 2015:16).

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CHAPTER 3 RESEARCH DESIGN

3.1 Introduction

The research methodology of the study followed a systematic literature review and data analysis approach. This study was conducted in three phases, which satisfied the research objectives. The first stage of the study was to conduct an extensive literature study on the relevant theories, concepts, and calculations to understand the cost implications of pump efficiency degradation. The second phase was to analyse the data of a pump station in a deep-level mine, to test the theories reviewed in the literature study. The data analysis was done to determine if the theories can be successfully applied in a deep-level mine environment. Lastly, the results obtained from the data analysis were compared with the theories highlighted in the literature, to conclude the study and recommend contributions to the existing literature.

3.2 Research methodology

3.2.1 Literature review

A literature review is a crucial component of academic research because prior existing studies must be used to advance academic knowledge. When conducting a systematic literature review, the research methodology will consist of an inclusion criterion, literature identification, screening for inclusion, quality assessment, iterations, and data extraction and analysis (Xiao & Watson, 2019:93).

The relevant literature was identified through key term searches, such as “pump efficiency degradation”, “ pump efficiency calculation”, “pump efficiency improvement”, and “pump performance measurement.” Google Scholar was used as the primary search engine. The title and abstract of each study indicated the relevance to the literature. The full studies were read, to include in the literature, as well as indicate additional literature required. Additional literature was indicated from the initial studies, which were researched with key terms like: “pump performance characteristics”, “mine-water reticulation systems”, “condition monitoring”, “efficiency valuation”, “data-driven methodology”, and “energy efficiency and savings calculations.” The final quality screening of all the relevant studies was done by considering if the studies were published by well-known sources. Books and journal articles published by reputable publishers were deemed as high-quality research and were therefore included in the final study. From each study, the information relating to the topics presented in chapter 2 was extracted, analysed and presented in the final literature review. A total number of 38 studies were deemed relevant, from which data were extracted and presented in the comprehensive literature review.

3.2.2 Empirical study

Most research is planned based on the problem that requires solving or the research question that requires answering. However, data collection and analysis need to be done to solve the research problem or answer the question. Data analysis procedures and data collection techniques can only be determined by following a sequence of steps (Saunders *et al.*, 2016:122). The data analysis procedures and data collection techniques are at the centre of the research 'onion' described by Saunders *et al.* (2016:122). The outer layers of the research 'onion' must be understood and explained to reach the centre and comprehensively cover the empirical study (Saunders *et al.*, 2016:122).

A sequence of sub-divisions (layers of the research 'onion') of the research design must be determined successfully to complete the empirical investigation of the study (Saunders *et al.*, 2016:122). The following sections of the research design were determined:

- Research paradigm
- Research approach
- Methodological choice
- Time horizon
- Study population and sampling
- Designing the measuring instrument
- Collection of data
- Data analysis

Each of these sub-divisions was determined as described in the sections to follow.

3.2.3 Research paradigm

Five major research paradigms or philosophies exist in management and business research: interpretivism, positivism, pragmatism, postmodernism, and critical realism (Saunders *et al.*, 2016:135). However, (Collis & Hussey, 2013:43) indicates that the most dominant research paradigms or philosophies in the field of management and social sciences are interpretivism and positivism. People's assumptions and philosophies of the world are the basis for a research design; therefore, the research design and the methods that people use to conduct their research are influenced by their assumptions and philosophies (Collis & Hussey, 2013:43). Positivism can be referred to or defined as something that is given or posited. Positivism focuses on strictly scientific and empirical methods that are designed to deliver facts and data that are not biased or influenced by interpretation (Saunders *et al.*, 2016:136). Interpretivism is a critique of positivism, but it differs slightly since a perspective is formed subjectively. Interpretivism focuses on human beings and argues that the social world of humans can't be analysed and studied in the same manner as phenomena presented by the physical world (Saunders *et al.*, 2016:140).

Primary scientific data was analysed using empirical analysis to achieve the primary and secondary objectives of the study. The empirical analysis was done without any bias or human interpretation, and therefore the research paradigm of the study followed a positivism paradigm.

3.2.4 Research approach

The inductive research approach moves from the particular to the general by forming theories and concepts based on empirical observations made on some phenomenon. The deductive research approach proceeds from the general to the particular by deriving a hypothesis or hypotheses from a theory and then testing the hypotheses and improving the original theory (Woiceshyn & Daellenbach, 2018:185). Any theoretical base can be used to start the deductive research approach. The theoretical base is used to deduce any number of hypotheses (Woiceshyn & Daellenbach, 2018:186).

The research approach of the study is deductive since a positivistic research paradigm was adopted, and the study tests a predetermined hypothesis. The hypothesis is that deep-level mines in South Africa experience financial losses caused by increased electricity consumption as a result of pump efficiency degradation.

3.2.5 Methodological choice

Qualitative and quantitative research can be distinguished from each other by the type of data being analysed. Qualitative research is a method to research non-numeric data, while quantitative research analysis numeric data (Saunders *et al.*, 2016:165). The outcome of a quantitative research study can be reached by analysing numerical data collected during the study. Analysing data aims to reveal underlying trends, patterns and relationships among variables in the study's context (Albers, 2017:1).

The methodological choice for this study is a quantitative research choice since the research paradigm is positivistic and numerical data was collected. The research choice can be better defined as technical/financial because the primary information is numerical values obtained from instrumentation measurements. The primary data was analysed and developed into a mathematical model to test the predetermined hypothesis. The secondary data is financial data used as variables in the mathematical model to satisfy the study's primary objective.

3.2.6 Time horizon

The time horizon of a study is described by Melnikova (2018:29) as the study's time frame. Data collection at a specific time interval is known as a short-term or cross-sectional study. In contrast, the repeated collection of data over a long period is a longitudinal study (Melnikovas, 2018:29).

The time horizon of the study is a longitudinal study design because a fixed set of variables was observed and analysed over time. The time interval between the data points is 10 minutes for pump performance data and 30 minutes for motor demand data with a time range of three years.

3.2.7 Designing the measurement instrument

Due to the technical nature of the data, two types of measuring instruments will be used to extract the data from the two types of sources. The first measuring instrument will be a Microsoft Structured Query Language (SQL) query that will extract pump performance data from the mine's SCADA historian. Each measured variable is given a unique identification (tag). The tags will be programmed into the SQL programme to extract the data points for the specific tags. The second measuring instrument will be a query program built into the electricity demand and tariff server that will be used to extract the required data. Each pump motor feeder has a unique identification (tag) selected in the program to export the historical demand data of the specific tag.

3.2.8 Data collection

The data used in this study is primary data sourced from a well-known deep-level gold mine in South Africa. The data used in the study are different types of data sourced from three different sources. The three data types are pump performance data, electrical demand data and electricity tariff data. The data extracted for this study was from June 2019 to May 2022, as not all the required data is available before June 2019. The data required for the study was not available on all the pump stations in the mine. There was only one pump station with all the required data, to do a comprehensive analysis. Therefore the data used in this study is on a specific pump station situated in a specific shaft in the mine.

3.2.8.1 Pump performance data

The data was extracted directly from the historical data server of the mine, using a Microsoft SQL query as shown in **Error! Reference source not found.**. The data is not p ublically available, and therefore special permission was granted by the mine to access the data. Since the data is recorded continuously, any time series can be specified from a one-second interval up to multiple-hour intervals. The data can be extracted in two different methods. The first is an average value over the specified time series, for example, the average value over a 10-minute interval. The second method is to extract the exact measured value on the specified timestamp, for example, the value measured at 2021/03/05 10:15 AM. The historical data is available as long as the variable has been measured. Most of the variables on the mine have been actively measured since 2018. Therefore most of the data is available from 2018 to date. The data extracted for this study was was average values of 10-minute intervals from 01 May 2018 at 00:00 AM to 08 May 2022 at 11:50 PM. The data was pasted into Microsoft Excel for further data analysis. The total number of data points extracted for the pump performance was 3,173,040 data points.

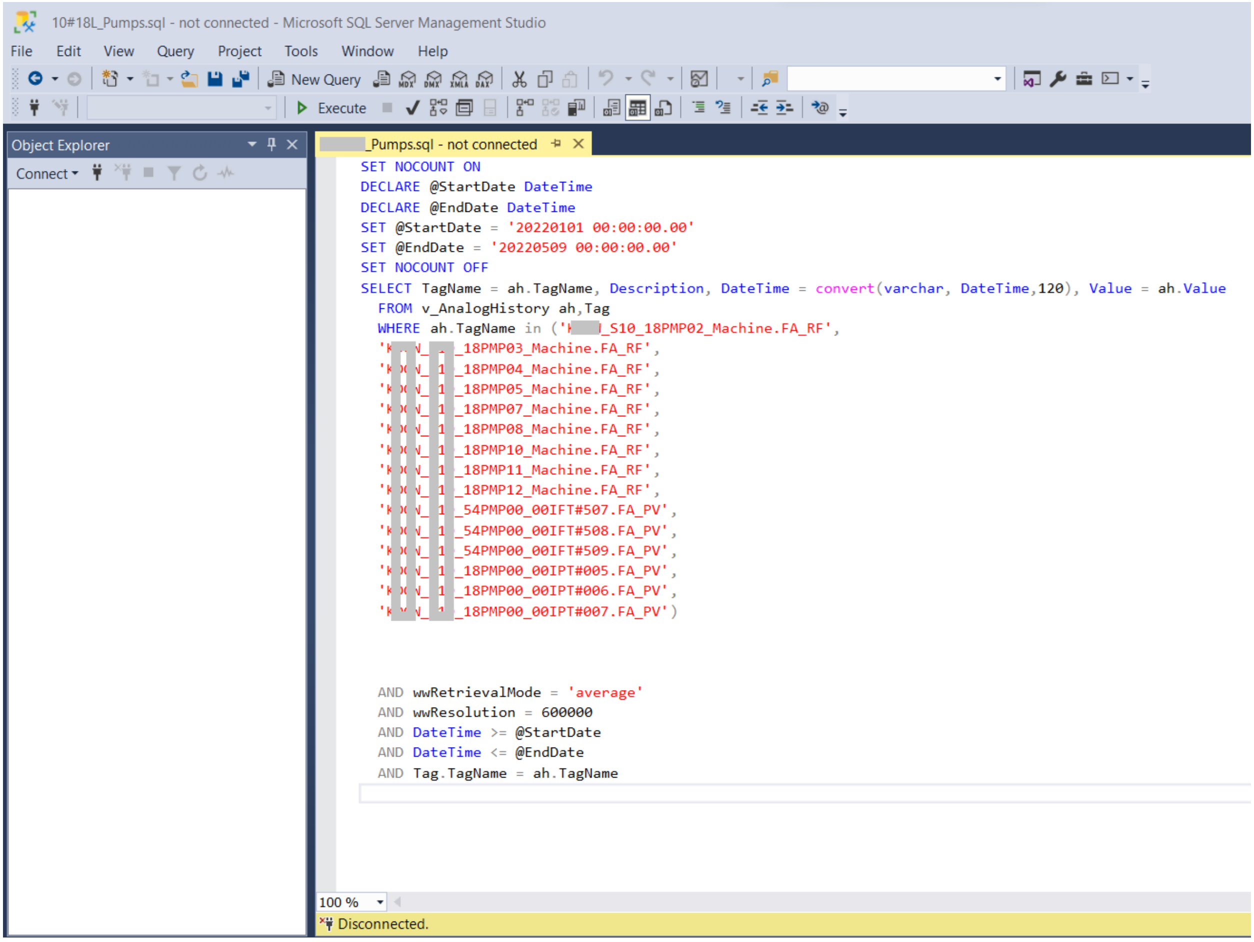

Figure 3-1: An example of a SQL query

3.2.8.2 Electrical demand data

The mine where this study was conducted purchases electricity from ESKOM. The electricity is supplied by ESKOM to the mine's point of delivery (POD) substations via incomers. From the substations, the mine distributes the electricity via metering panels to surface and underground feeders. Individual consumers like pumps, compressors, fans and other auxiliary equipment are supplied from the feeders. The electricity consumption is measured in the mine with metering equipment. All the incomers, feeders and some of the individual equipment are continuously measured. The energy data measured is stored on the mine's server in 30-minute intervals. The energy consumption for any meter can be extracted from the server. A third-party company is contracted by the mine to manage the integrity of the metering data and metering network equipment. The energy data can be accessed on the mine's server through a data interface named Energy Insight (EI). **Error! Reference source not found.** shows the EI interface used to view and extract the m ine's electricity demand data. Each metering component has a specific tag, that can be selected to view the electricity consumption of the specific incomer, feeder or equipment. The data can be extracted to a Microsoft Excel sheet for data analysis.

The electricity demand data used for this study was extracted from the mine's server via the EI interface. The specific pump station analysed in this study has power meters on each pump within the pump station. Each pump's tag was selected in EI, and the data was extracted to Microsoft Excel for data analysis. The energy data was extracted in 30-minute intervals from 01 May 2018 at 00:00 AM to 08 May 2022 at 11:30 PM. The total number of data points extracted for the electrical demand was 1,903,824 data points.

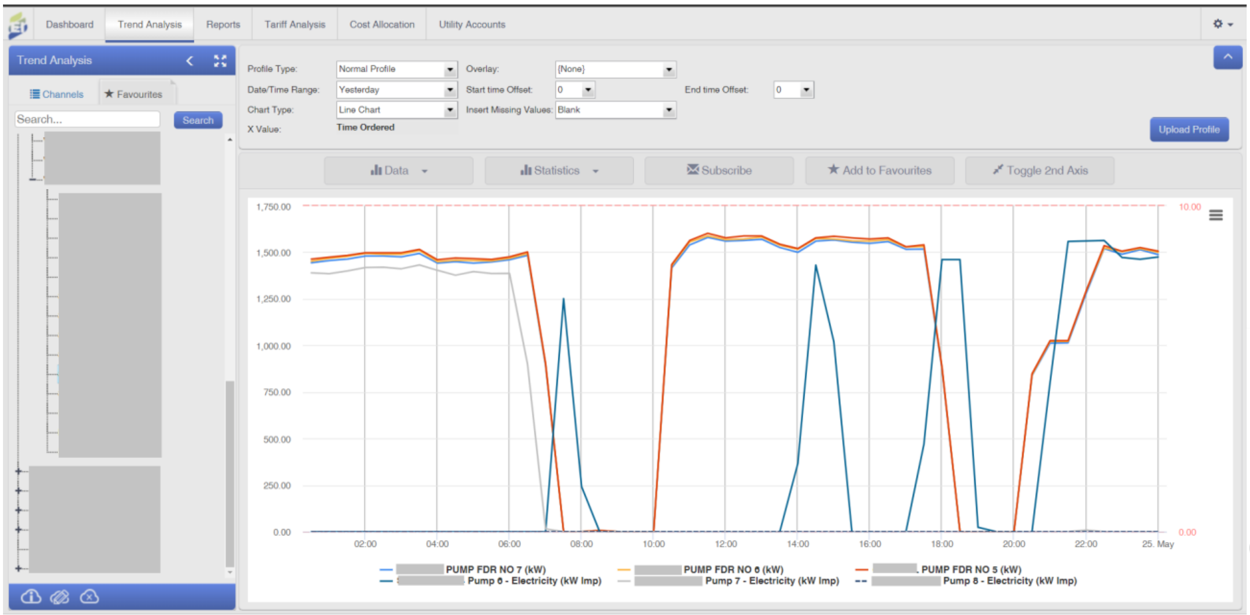

Figure 3-2: Energy Insight data management interface

3.2.8.3 Electricity tariff data

The electricity consumed by the mine is billed monthly by ESKOM to the mine. The electricity consumed by the mine is billed by ESKOM on the electricity consumed on the incomer's level. ESKOM has metering equipment installed at the mine's incomers. The billing energy consumption is billed based on the energy consumed as per ESKOM's metering equipment. The third-party contracted by the mine to manage the integrity of the mine's energy consumption is also contracted to manage the integrity of the mine's energy tariffs. The contracting company matches the mine's incomer metering equipment with ESKOM's metering equipment, to ensure the billing can be divided correctly to all the consumers. The bill is broken down into all the different charges and allocated to each metering component based on their specific consumption for the billed month. The billing is done on a monthly bases. The billing breakdown is stored on the mine's server and can be extracted via the EI interface.

The monthly cost breakdown of the pump station analysed in this study was extracted from the EI interface. Each month's cost breakdown from May 2018 to April 2022 was extracted. The energy tariff for each month was calculated from the cost breakdown. Figure 3-3 shows a cost breakdown of a single feeder as presented on EI.

Tariff Component	Rate	Unit	Reading	Cost	Date	Adj Reading	Adj Cost
Administration Charge	186.8500	R/c	30.0000	R 5 605.50			R 379.99
TX Network Capacity Charge	11.9600	R/kVA	17 500.0000	R 209 300.00	Utilised Capacity not exceeded	818.1155	R 9 784.66
Network Capacity Charge	23.8500	R/kVA	17 500.0000	R 417 375.00	Utilised Capacity not exceeded	818.1155	R 19 512.06
Network Demand	45.2400	R/kVA	1 195.0113	R 54 062.31	2022-04-04 21:00	984.2064	R 44 525.50
Excess Network Capacity Charge	35.8100	R/kVA	.0000	R .00	2022-04-04 21:00	.0000	R .00
Ancillary Service Charge	0.0059	R/kWh	331 486.0000	R 1 955.77		332 273.7037	R 1 960.41
Off-Peak Energy - High Demand	0.7409	R/kWh	.0000	R .00		.0000	R .00
Off-Peak Energy - Low Demand	0.6414	R/kWh	209 338.0000	R 134 269.39		209 824.4915	R 134 581.43
Peak Energy - High Demand	4.5029	R/kWh	.0000	R .00		.0000	R .00
Peak Energy - Low Demand	1.4687	R/kWh	2 644.0000	R 3 883.24		2 639.1551	R 3 876.13
Standard Energy - High Demand	1.3641	R/kWh	.0000	R .00		.0000	R .00
Standard Energy - Low Demand	1.0110	R/kWh	119 504.0000	R 120 818.54		119 821.1691	R 121 139.20
Affordability Subsidy	0.0569	R/kWh	331 486.0000	R 18 861.55		332 273.7037	R 18 906.37
Electrification Subsidy	0.1163	R/kWh	331 486.0000	R 38 551.82		332 273.7037	R 38 643.43
Excess Reactive - High Demand	0.2103	R/kVArh	.0000	R .00		.0000	R .00
Excess Reactive - Low Demand	0.0000	R/kVArh	6 971.6000	R .00		.0000	R .00

Figure 3-3: Feeder monthly cost breakdown

3.2.9 Study population and sampling

Any research study would benefit from assessing the problem across the entire population. However, studying the whole population is not always feasible in practice. Alternately, a sufficiently large and representative sample of the population is analysed.

The sample consists of a subset of the total population selected to reflect the general population (Acharya *et al.*, 2013:330).

The study population is all the pumps in the deep-level hard rock gold mines in South Africa. Since different companies own the mines, some of the mines were not accessible to the researcher, therefore the population was reduced to mines owned by a single organisation. The study population was reduced to an accessible population consisting of three mines in the Witwatersrand Basin. Due to the high volume of the data, it was not possible to use the entire population (accessible population) for the study, and therefore a sample was used. A sampling process was used to select the sample. Inclusion criteria were used to determine the pump stations that formed part of the study. The following inclusion criteria were used to select the sample:

- Pumps must form part of a high-head pump station (higher than 500m)
- All the required data must be measured and available for at least two years

Once the inclusion criteria were applied to the various pump stations, only one pump station met the criteria, primarily due to the comprehensive historical data measured. The pump station selected for this study had a complete set of data measured continuously for three years.

3.2.10 Data analysis

Due to the nature of the study, the data analysis is not statistical but rather mathematical. The data analysis followed a sequence of mathematical methods to develop the empirical model which was used to achieve the objectives. The sequence of mathematical methods included data sorting, a time series plot, data cleaning, data imputation, baseline model development, prediction model development, model comparison and financial loss prediction. The sequence of mathematical methods is described in the sections to follow. The method described by Reichl and Kollmann (2011:423) for calculating gross financial losses of a proposed energy efficiency improvement was used as the bases for the data analysis. The mathematical method is described in section 2.9 of the literature chapter. The principle of forecasting models as described by Montgomery *et al.* (2015) was used to analyse the existing data and develop the baseline models.

Forecasting is vital because predicting future events is essential to decision-making and planning processes (Montgomery *et al.*, 2015:3). It was required to make forecasts on several variables to achieve the study's objective of predicting the energy consumption of the pump station if the pumps operated at a higher efficiency. A medium-term forecasting model was developed to determine the existing energy consumption and predict the theoretical energy consumption for refurbished pumps. Medium-term forecasting is frequently based on extrapolating, modelling and identifying the patterns present in historical data (Montgomery *et al.*, 2015:2).

The technique that was used for the development of the forecasting model is a quantitative forecasting technique. Quantitative forecasting techniques formally use historical data and forecasting models, to sum up, patterns in the historical data to indicate a relationship between current and previous values of a variable. The forecasting model extrapolates current and past data behaviour into the future (Montgomery *et al.*, 2015:5). The quantitative forecasting model that was developed is a general time series model.

The statistical properties of historical data are employed in a general time series model to specify a formal model and then estimate the unknown parameters of the model (Montgomery *et al.*, 2015:5). Several steps were followed to develop the time series forecasting model and estimate the model's unknown parameters.

3.2.10.1 Data sorting

The data was collected from different sources and therefore was presented in various formats. The pump performance data collected from the mine's historical server was in a continuous string. The data had to be sorted to be able to plot a time series. The data was extracted into a Microsoft Excel file to sort the data and do data processing. The data was sorted with pivot tables in Microsoft Excel to achieve the desired format for further processing.

3.2.10.2 Time series plot

A graphical display and analysis of the data should be the first step in developing a forecasting model (Montgomery *et al.*, 2015:14). The data was plotted on a time series plot to identify patterns like cyclical components, seasonal components, and trends as well as identify data errors. Data errors include data that does not fall within the expected range, missing data and potential outliers. Along with time series plots, scatter plots were used to determine the correlation between two variables like the energy consumption and volume flow rate of a pump, to identify data outliers. If patterns were not evident in the time series plots, a smoothed version of the data was overlayed on the time series to help reveal patterns in the data.

3.2.10.3 Data cleaning

After the data was plotted on a time series plot and the data errors were identified, data cleaning was done to correct the data errors. Data errors could result from transmission or recording errors and can be rectified by using the data in the original data source to fix the problem (Montgomery *et al.*, 2015:18). Data errors occurred when a flow meter measured an error. The data errors were corrected by placing the data in a Microsoft Excel sheet and doing data imputation.

3.2.10.4 Data imputation

The process of replacing outliers and correcting missing data with estimation values is called imputation. Regression imputation is a form of mean value imputation. The imputation value is calculated from a regression model or a time series model. The value calculated with the model replaces the outliers and missing data. (Montgomery *et al.*, 2015:18). The data was cleaned by replacing the errors with a value calculated with the time series model. The data errors were corrected by replacing the missing volume flow rate data with the average volume flow rate measured before and after the missing data.

3.2.10.5 Baseline model development

After the data have been cleaned and transferred to a time series arrangement, baseline performance models were developed. The baseline models include the volume of water pumped, the energy consumption, the efficiency and the utilisation of individual components. The baseline models were developed on multiple levels, to ensure a holistic understanding of the pumping system. The three levels of baseline models developed are the whole pump station, the individual columns within the pump station and the individual pumps within the pump station. The literature revealed that the energy efficiency of pumping systems can be calculated in terms of energy consumption per volume of water pumped (kWh/Ml). The energy consumption per volume of water pumped was determined to determine the baseline cost irrespective of the volume of water pumped.

3.2.10.6 Prediction model development

After the baseline efficiency models were developed, the individual pump efficiency was calculated in terms of the hydraulic method as described by the literature in section 2. The individual pump efficiency indicated the range of pump efficiency degradation. A single pump was identified that operates close to the theoretical BEP, and that pump's parameters were used as the theoretical refurbished pump. The parameters of the theoretical refurbished pump were used to develop a selective replacement model. The low-performance pumps' parameters were replaced with the parameters of the theoretical pump's parameters. After the replacement was done, the system performance and the operational cost were simulated to calculate the theoretical cost of the improved pump system.

3.2.10.7 Comparison model

The baseline model and prediction model were used to develop a comparison model as described by Reichl and Kollmann (2011:423). The comparison model was developed to compare the operational cost of the baseline model with the operational cost of the prediction model. The difference between the two models specifies the gross financial losses due to pump efficiency degradation in the pump station. The comparison model satisfies the primary objective.

CHAPTER 4 EMPIRICAL STUDY

4.1 Introduction

The literature revealed that the increasing energy cost places a strain on deep-level mining companies' competitiveness. The degradation of equipment efficiency has an impact on operational costs, since the energy consumption of the equipment increases. One of the largest consumers of electrical energy in deep-level mines is pumping systems. The pumping systems are an intricate part of the mining operations. As described by Eaton *et al.* (2018:1): the operational cost of a pump exceeds the initial cost of a pump, therefore throughout the pump's life, the long-term expenses brought on by the inefficiencies might be substantial. When the pump is operating, little is known about the performance change until a significant performance decline affects the system process that the pump is driving.

A well know deep-level gold mine in South Africa was identified to investigate the financial impact of energy losses due to pump efficiency degradation. A specific pump station within one of the mine's shafts was identified for the study. The specific pump station measures all the relevant parameters to calculate the pump efficiency as described by Stoffel (2015:11) and, Yates and Weybourne (2001:104-105). The measured parameters are primarily used by the mine for operational requirement measurement and partial predictive maintenance. The empirical study aimed to investigate if the mine's predictive maintenance strategy is sufficient, as it only considers pump performance and not financial losses incurred as a result of performance degradation. The results can be further used by all types of companies using pumping systems for improved condition monitoring and optimal predictive maintenance strategies.

4.2 Data analysis

4.2.1 Analysis 1: The whole pump station

The first analysis was done to determine the baseline parameters of the whole pump station. The pump station consists of nine multi-stage pumps, that run at different times to satisfy the operational demand. The baseline parameters that were calculated are the volume of water pumped, the demand consumed to pump the specific volume of water, the average system efficiency, the electricity tariffs, and the baseline cost. By calculating these parameters the average efficiency of the pump station can be calculated in kW/Ml (Kilowatt per Megalitre) as specified by Yates and Weybourne (2001:105). As there are small fluctuations in the daily requirements, the baseline parameters were calculated as an average per-day value.

4.2.1.1 Water pumped

The water pumped from the pump station was calculated as the average Ml/day per month. The water volume pumped was calculated as the average water pumped per day in a month, since different months have different numbers of days, which will skew the results if the total water pumped per month was calculated. Figure 4-1 below shows a graphical representation of the volume of water pumped per day from the pump station. The data from the flowmeters were only available from December 2018. The average amount of water pumped per day from the pump station was 20.6 Ml/ day with a maximum volume of 23.8 Ml/day pumped in September 2019, and a minimum volume of 18.7 Ml/day pumped in October 2021.

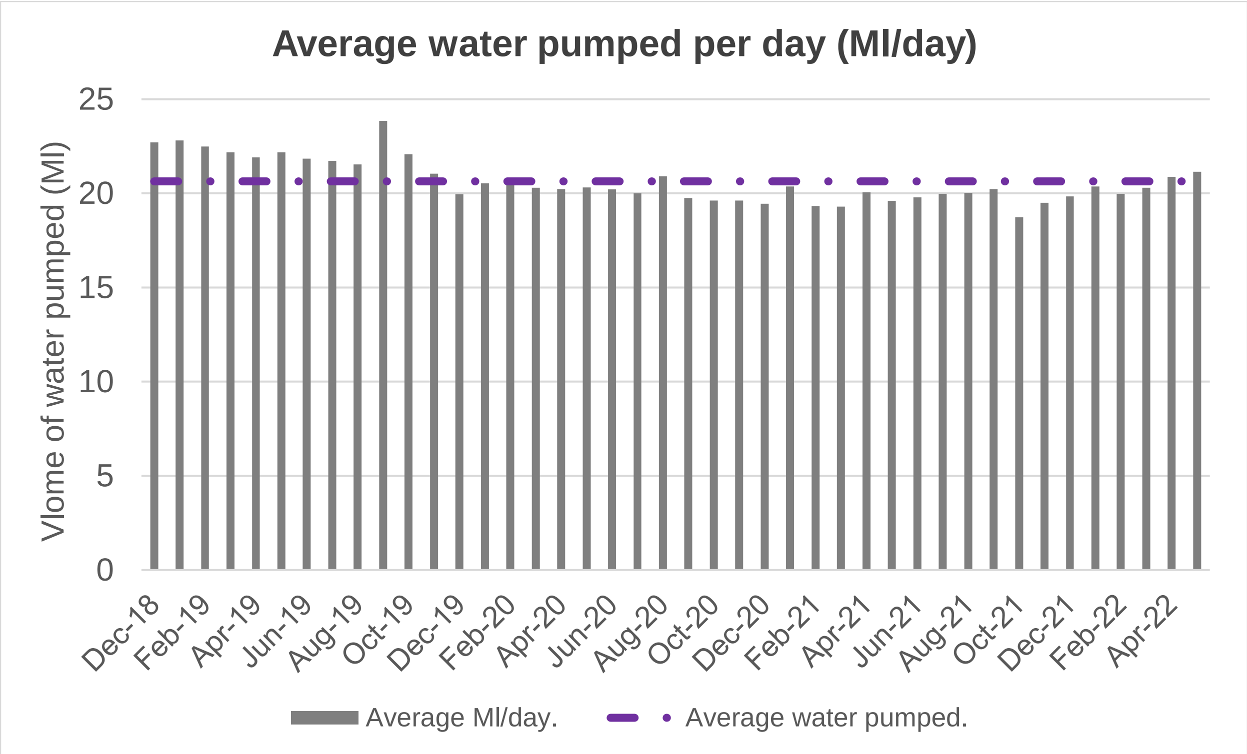

Figure 4-1: The average volume of water pumped per day

4.2.1.2 Energy demand

The energy consumed by the pump station was calculated as the average kW/day per month. The energy consumed was calculated as the average energy consumed per day in a month, since different months have different numbers of days, which will skew the results if the total energy consumed per month was calculated. Figure 4-2 below shows a graphical representation of the electrical energy consumed per day by the pump station. The data from the power meters were only available from May 2018. The average amount of electrical energy consumed per day by the pump station was 2771 kW/day with a maximum demand of 3347 kW/day consumed in August 2018, and a minimum demand of 2450 kW/day consumed in March 2021

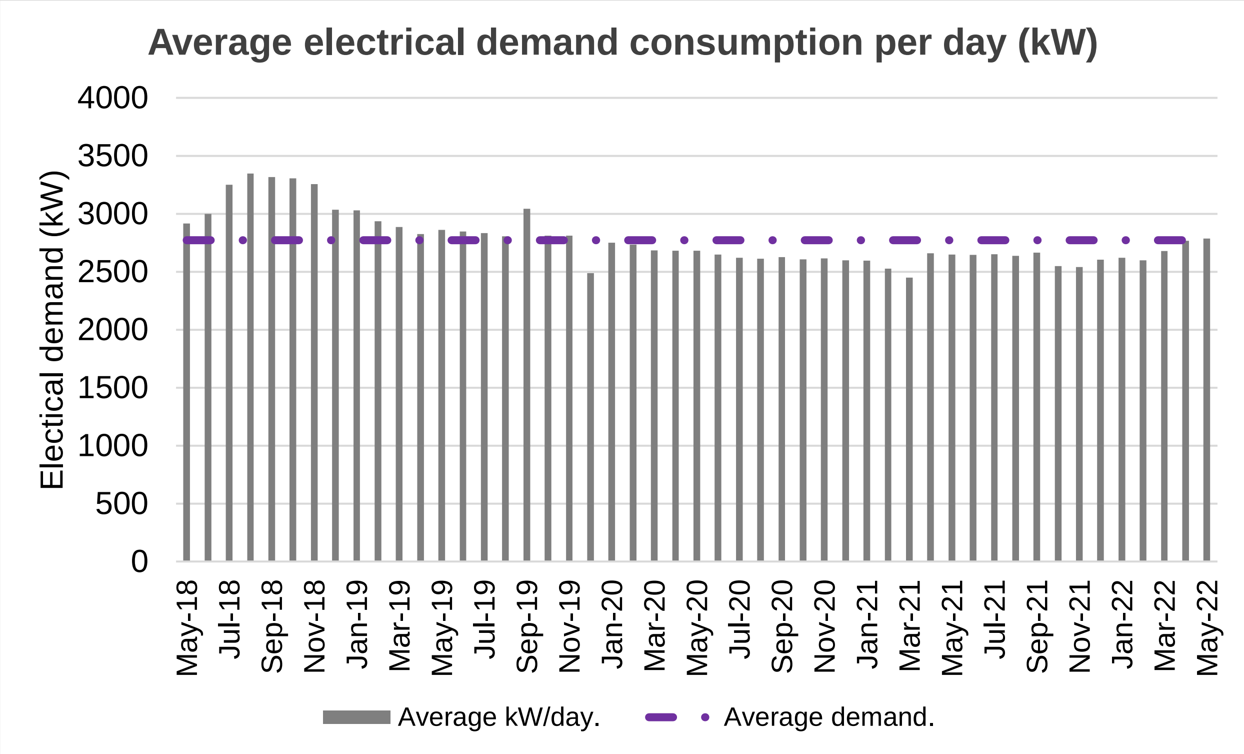

Figure 4-2: The average electrical demand consumption per day (kW)

4.2.1.3 System efficiency

By considering the pump station a single pump, the system efficiency was calculated to determine a high-level overview of the pump station's performance. The system efficiency was calculated with three methods. The first was the kWh/Ml as described by Yates and

Weybourne (2001:105). The second method is similar to the first method. The kWh/Ml was converted to a kW/Ml value. The last method was to consider the pump station as a large pump, to calculate the pump efficiency with formulas 2.16 and 2.18 as described by Stoffel (2015:11). The system efficiency of the pump station in terms of kWh/Ml, kW/Ml and the percentage is represented graphically in Figure 4-3, Figure 4-4 and Figure 4-5 respectively. The data from the power meters were only available from December 2018, since the flowmeter data was only available from December 2018. The average kWh/Ml efficiency was calculated as 3147 kWh/Ml, the average kW/Ml was calculated as 131 kW/Ml, and the average percentage pump efficiency was calculated as 74.3%.

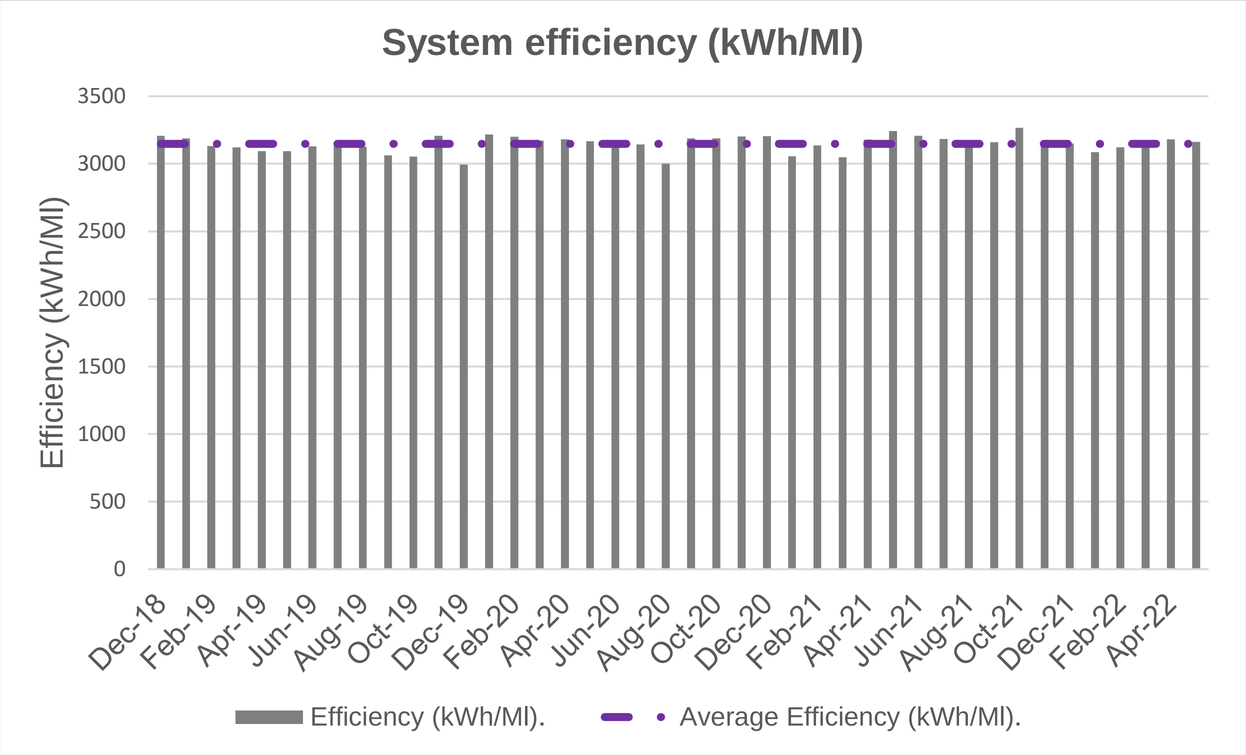

Figure 4-3: System efficiency (kWh/Ml)

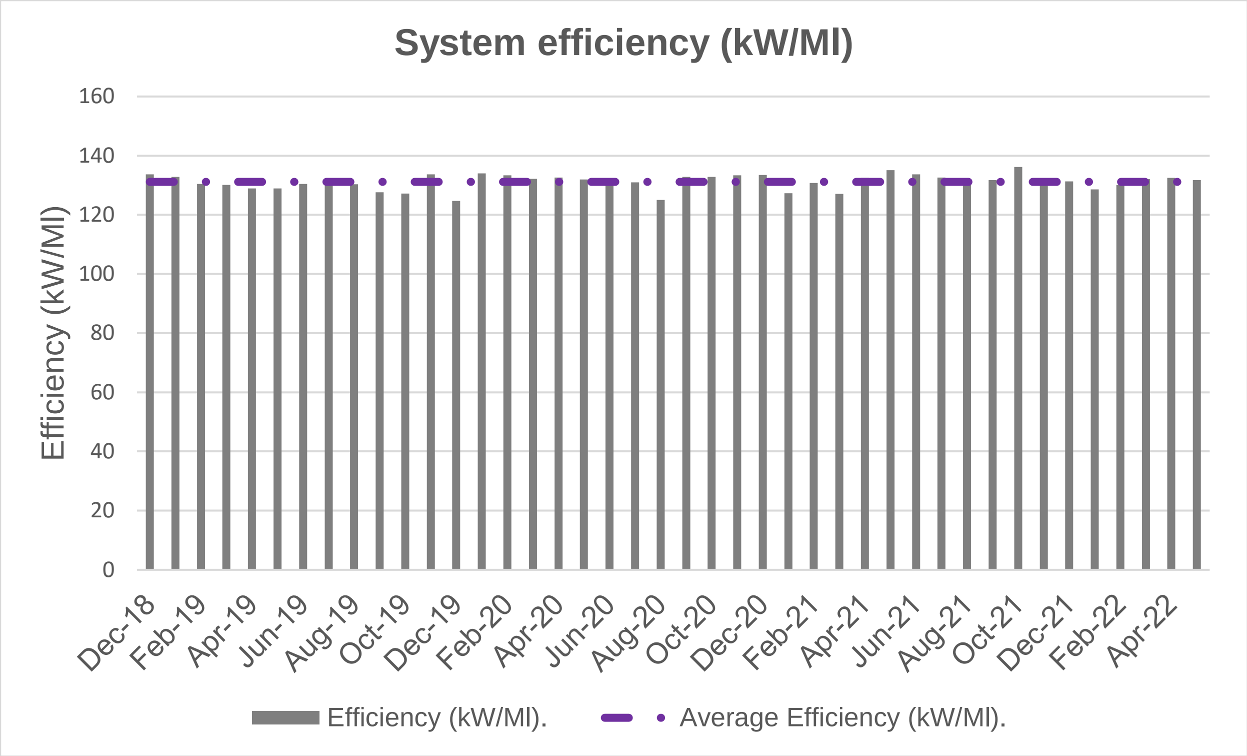

Figure 4-4: System efficiency (kW/Ml)

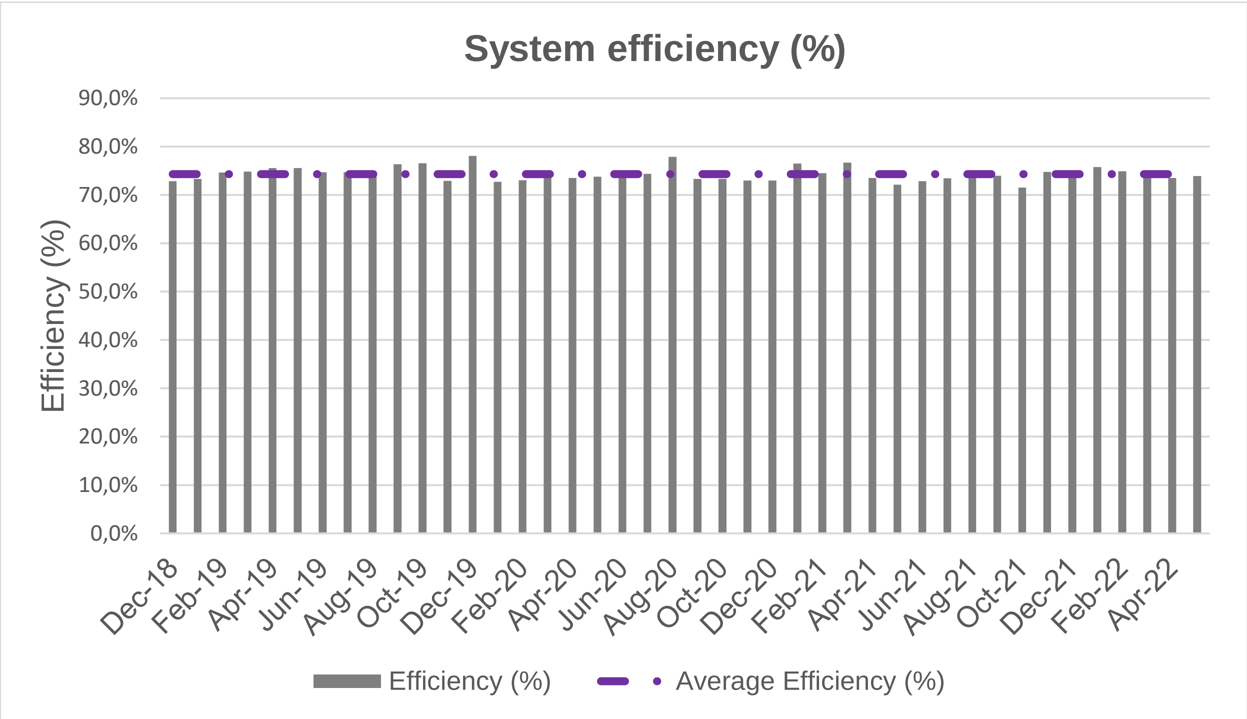

Figure 4-5: System efficiency (%)

4.2.1.4 Energy tariffs

The energy tariffs were obtained as described in section 3.2.8. The energy tariffs for the specific pump station were determined by calculating the cost per unit of energy consumed (R/kWh). The energy tariff for each month is influenced by various factors as described in section 2.10.3. The energy tariff per month and the average energy tariff per year are displayed in Figure 4-6.

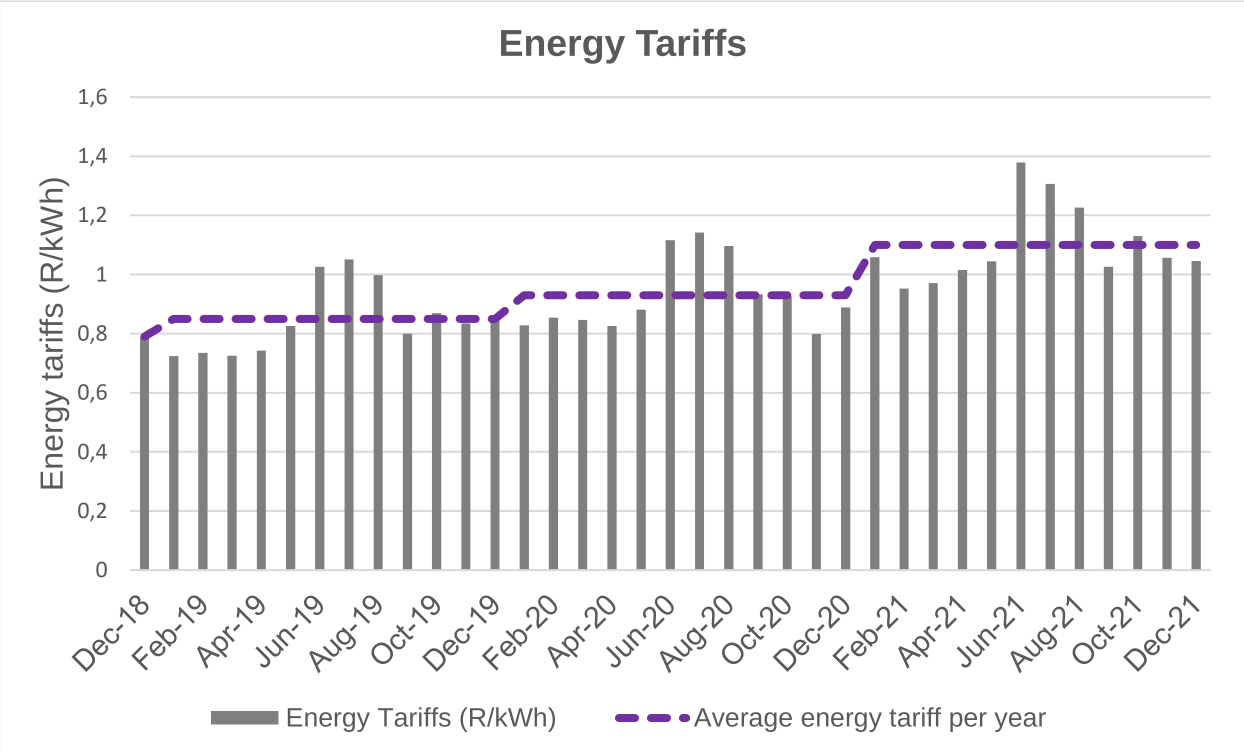

Figure 4-6: Monthly energy tariffs (R/kWh)

4.2.1.5 System baseline cost

The system baseline cost was calculated by multiplying the energy tariff with the energy consumed by the pump station. The system baseline cost was also presented as an effective cost per volume of water pumped, to compare different months with each other, regardless of the volume of water pumped during the month, and the number of days in the month. Figure 4-7 shows the monthly cost of the pump station, as well as the average monthly cost per year. Figure 4-8 shows the effective monthly cost of Rands per Megaliter (R/Ml) of water pumped, as well as the average effective monthly cost per year in R/Ml.

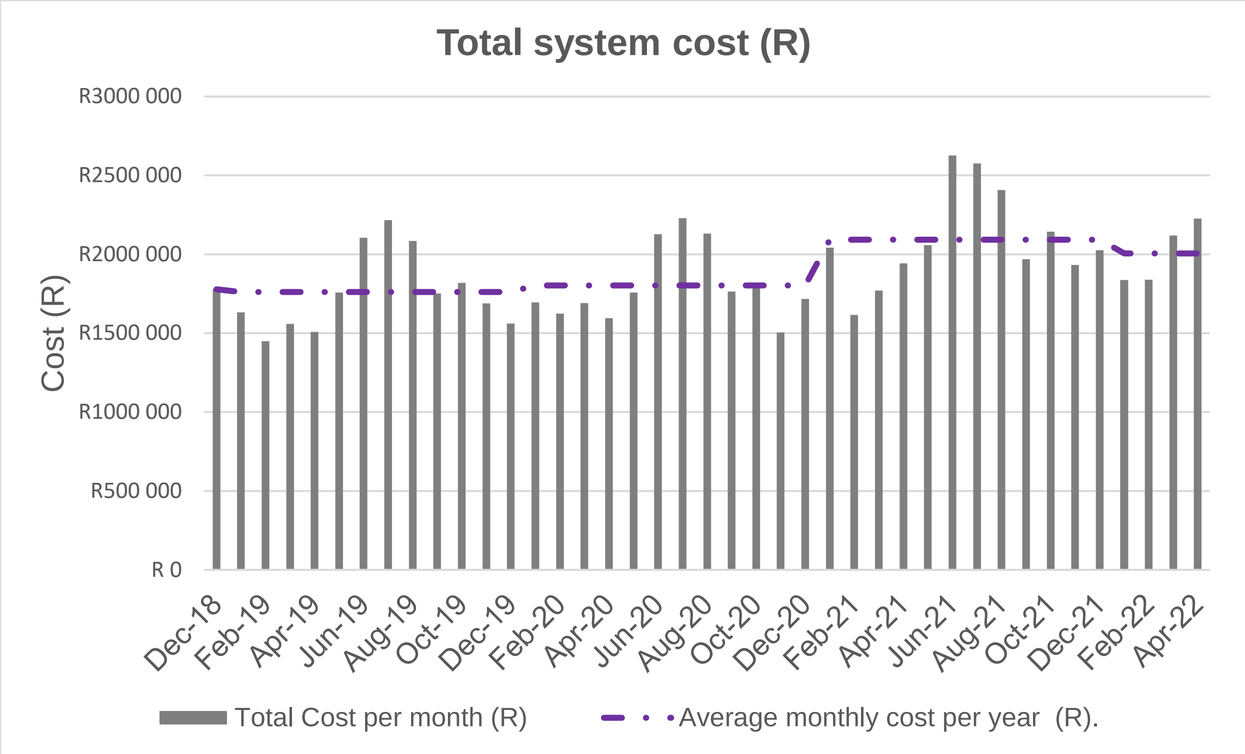

Figure 4-7: Monthly operational cost of the pump station

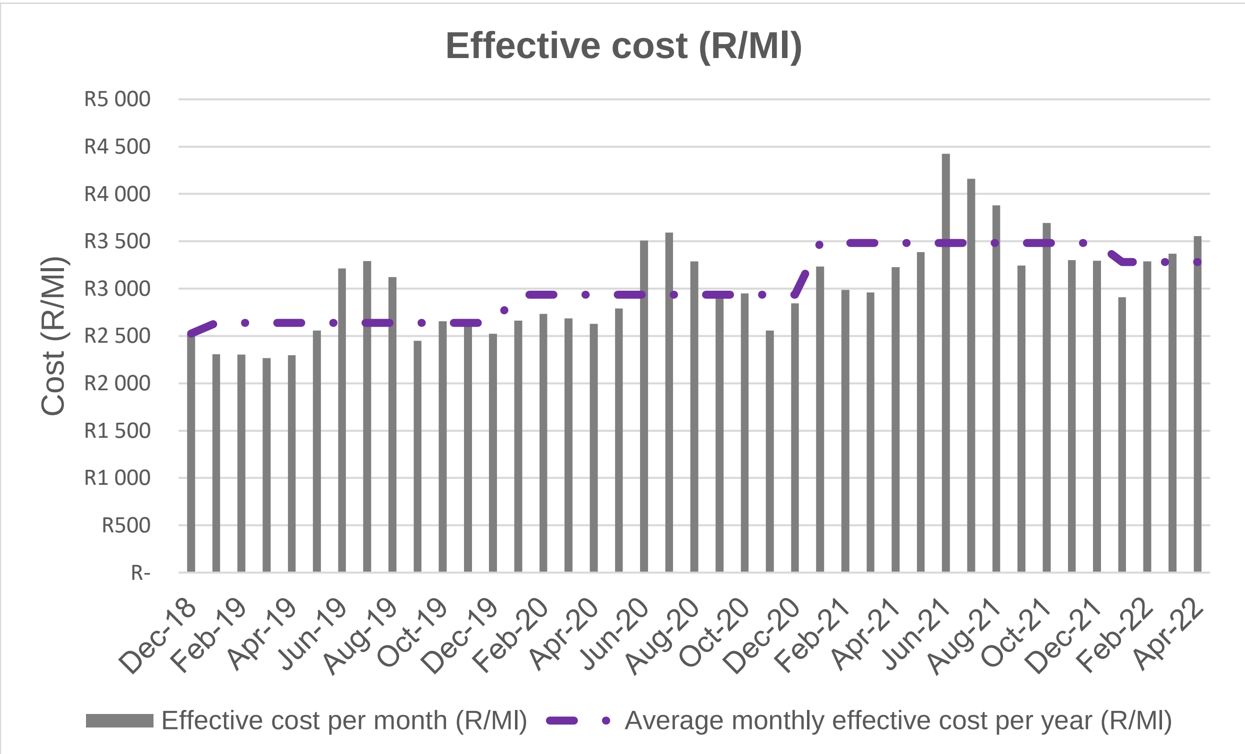

Figure 4-8: Monthly effective cost of the pump station (R/Ml)

4.2.2 Analysis 2: The pump columns within the pump station

The second analysis was done to give a more detailed breakdown of the pump station. The pump station consists of nine multi-stage pumps, that run at different times to satisfy the operational demand. The pump station consists of three pumping columns (Column 1,2,3). Each pumping column is connected to three pumps, that are run at different times; depending on pump and column availability. Figure 4-9 below displays the SCADA view of the pump station, to show the pumping columns connected to the pumps. Various parameters for each column were calculated to determine the contribution of each column to the total system performance. The parameters that were calculated are the volume of water pumped, the demand consumed to pump the specific volume of water, the average system efficiency, and the baseline cost. By calculating these parameters the average efficiency of each column can be calculated in kW/Ml (Kilowatt per Megalitre) as specified by Yates and Weybourne (2001:105). As there are small fluctuations in the daily requirements, the baseline parameters were calculated as an average per-day value.

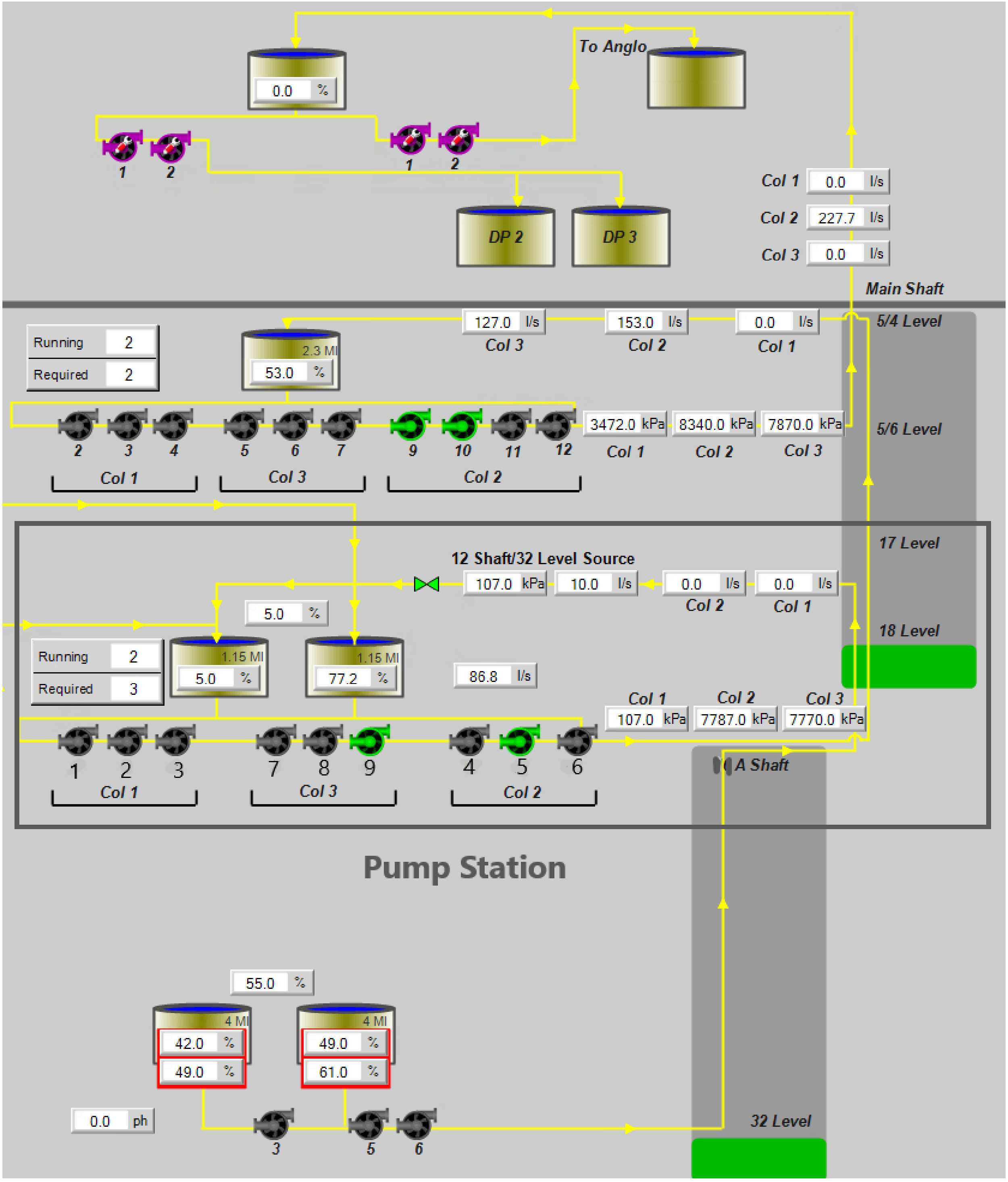

Figure 4-9: SCADA view of the pump station

4.2.2.1 Water pumped

The water pumped by each one of the three columns within the pump station was calculated as the average Ml/day per month. The water volume pumped was calculated as the average water pumped per day in a month, since different months have different numbers of days, which will skew the results if the total water pumped per month was calculated. Figure 4-10, Figure 4-11 and Figure 4-12 below show a graphical representation of the average volume of water pumped per day from columns 1, 2 and 3 respectively. The data from the flowmeters were only available from December 2018. The average amount of water pumped per day from columns 1,2 and 3 was 7.3, 9.1 and 4.3 Ml/day respectively.

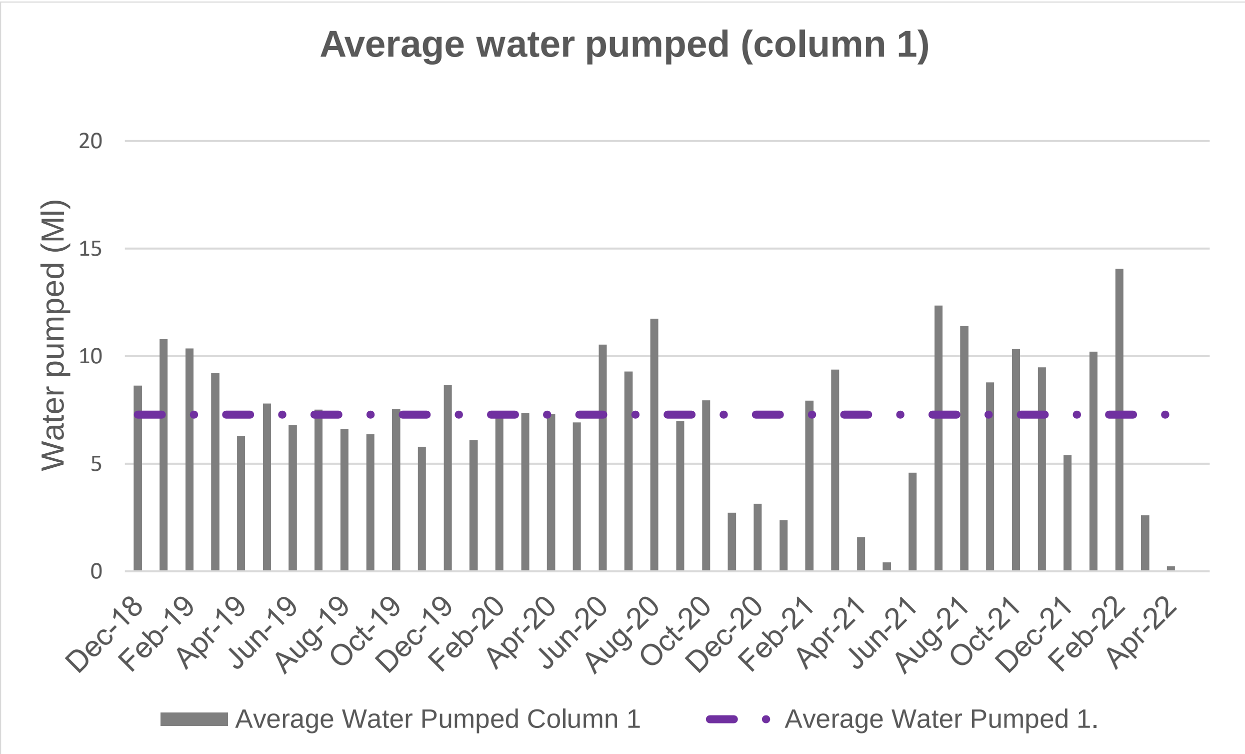

Figure 4-10: Average daily water pumped per month (Column 1)

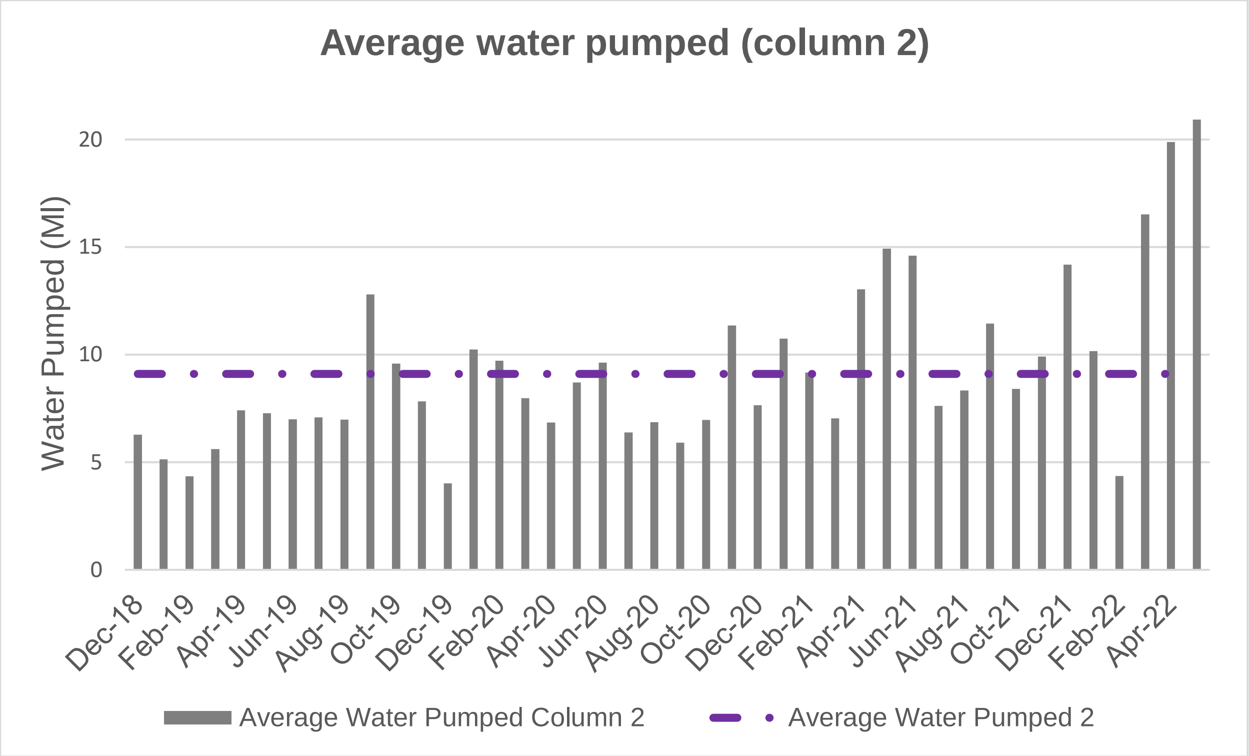

Figure 4-11: Average daily water pumped per month (Column 2)

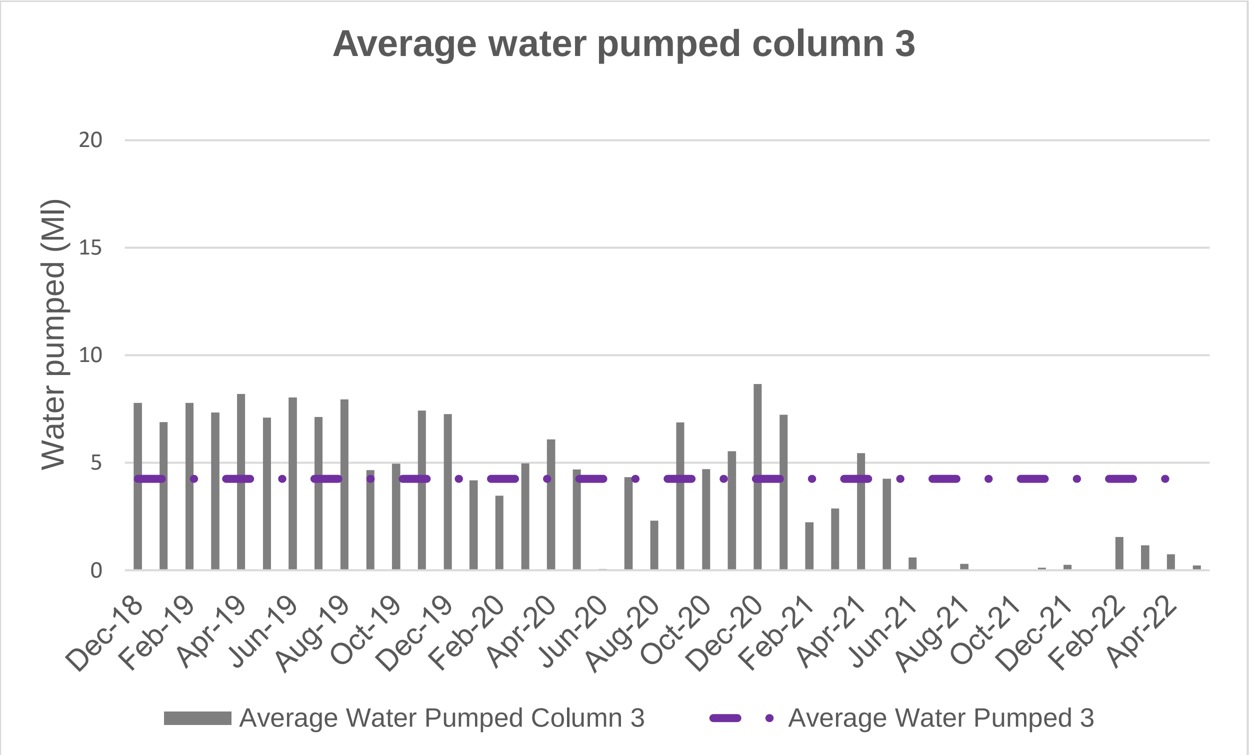

Figure 4-12: Average daily water pumped per month (Column 3)

4.2.2.2 Energy demand

The energy consumed by the pumps in each column was calculated as the average kW/day per month. The energy consumed was calculated as the average energy consumed per day in a month, since different months have different numbers of days, which will skew the results if the total energy consumed per month was calculated. Figure 4-13, Figure 4-14 and Figure 4-15 below show a graphical representation of the electrical energy consumed per day by pumps in columns 1,2 and 3 respectively. The data from the power meters were only available from May 2018. The average amount of electrical energy consumed per day by columns 1, 2 and 3 was 900.2, 1176.7 and 693.9 kW respectively.

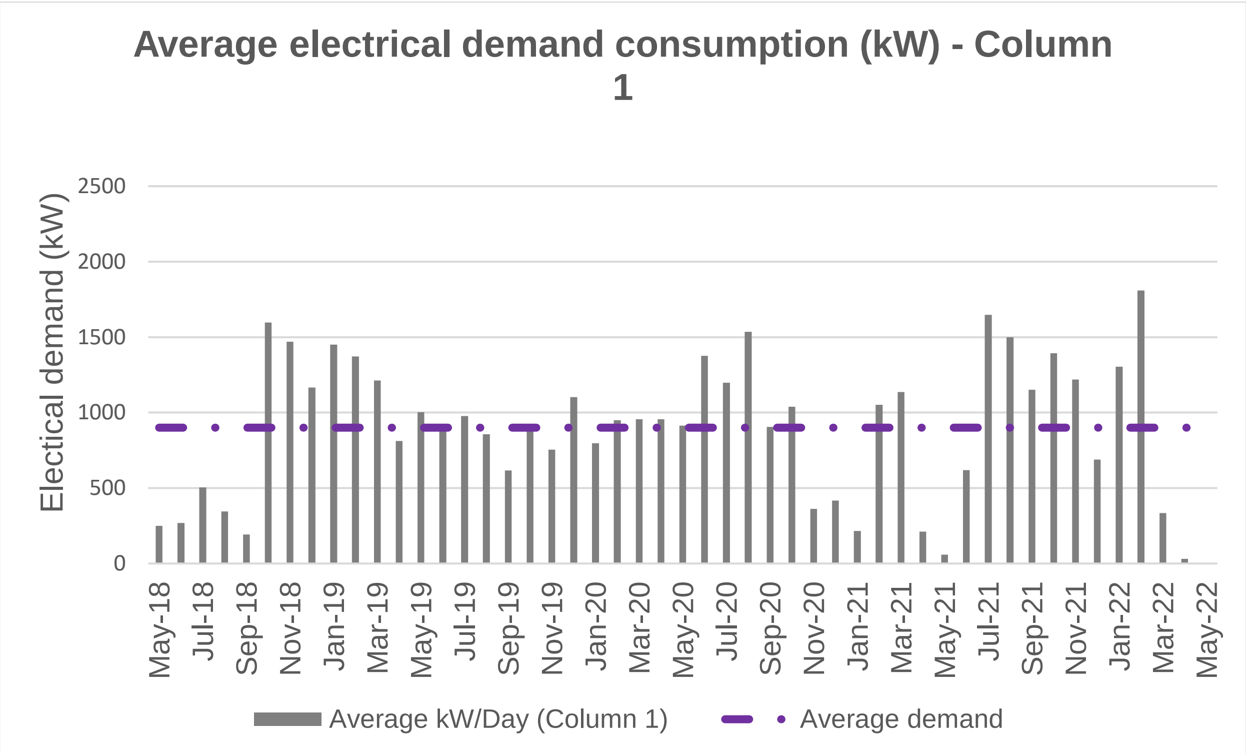

Figure 4-13: Electrical energy consumed per day (Column 1)

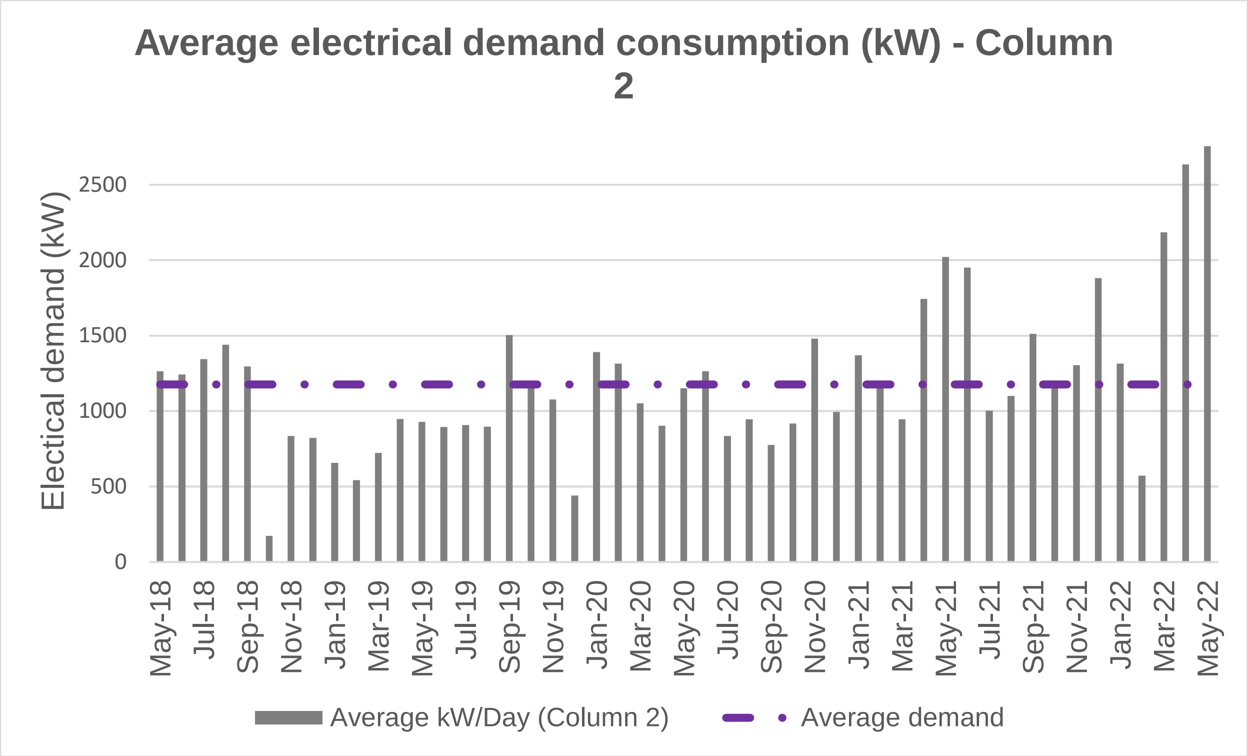

Figure 4-14: Electrical energy consumed per day (Column 2)

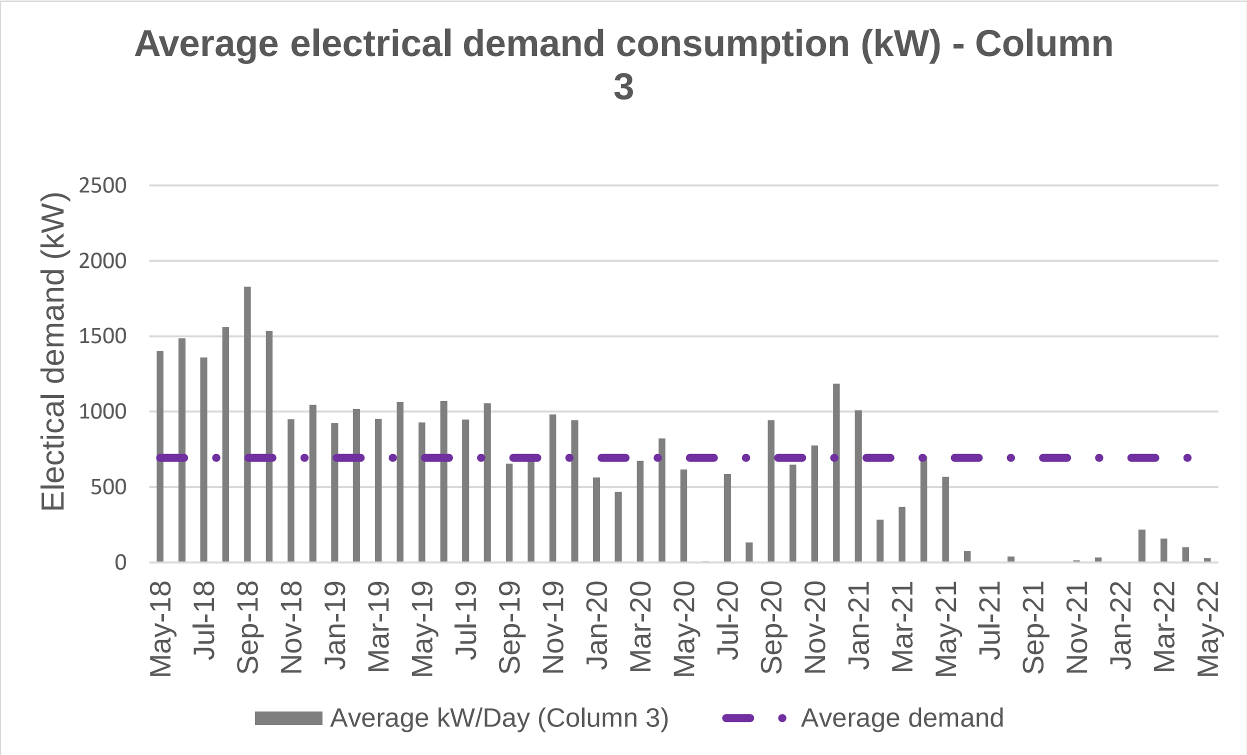

Figure 4-15: Electrical energy consumed per day (Column 3)

4.2.2.3 Pump column efficiency

By considering each column as a single pump, the column efficiency was calculated to determine a high-level overview of each column’s performance. Each column’s efficiency was calculated with three methods. The first was the kWh/Ml as described by Yates and Weybourne (2001:105). The second method is similar to the first method. The kWh/Ml was converted to a kW/Ml value. The last method was to consider each column as a large pump, to calculate the pump efficiency with formulas 2.16 and 2.18 as described by Stoffel (2015:11). Each column's efficiency in terms of kWh/Ml is presented graphically in Figure 4-16, Figure 4-17, Figure 4-18, the efficiency in terms of kW/Ml is presented graphically in Figure 4-19, Figure 4-20 and Figure 4-21, and the efficiency in terms of pump efficiency (%) is presented graphically in Figure 4-22, Figure 4-23 and Figure 4-24. The data from the power meters were only available from December 2018, since the flowmeter data was only available from December 2018. The average kWh/Ml for columns 1,2 and 3 was calculated as 3144.1, 3156.2 and 3221.1 kWh/Ml respectively. The average kW/Ml for columns 1,2 and 3 was calculated as 131.0, 131.5 and 134.2 kWh/Ml respectively. The average percentage efficiency (%) for columns 1,2 and 3 was calculated as 74.4%, 74.1% and 72.6% respectively.

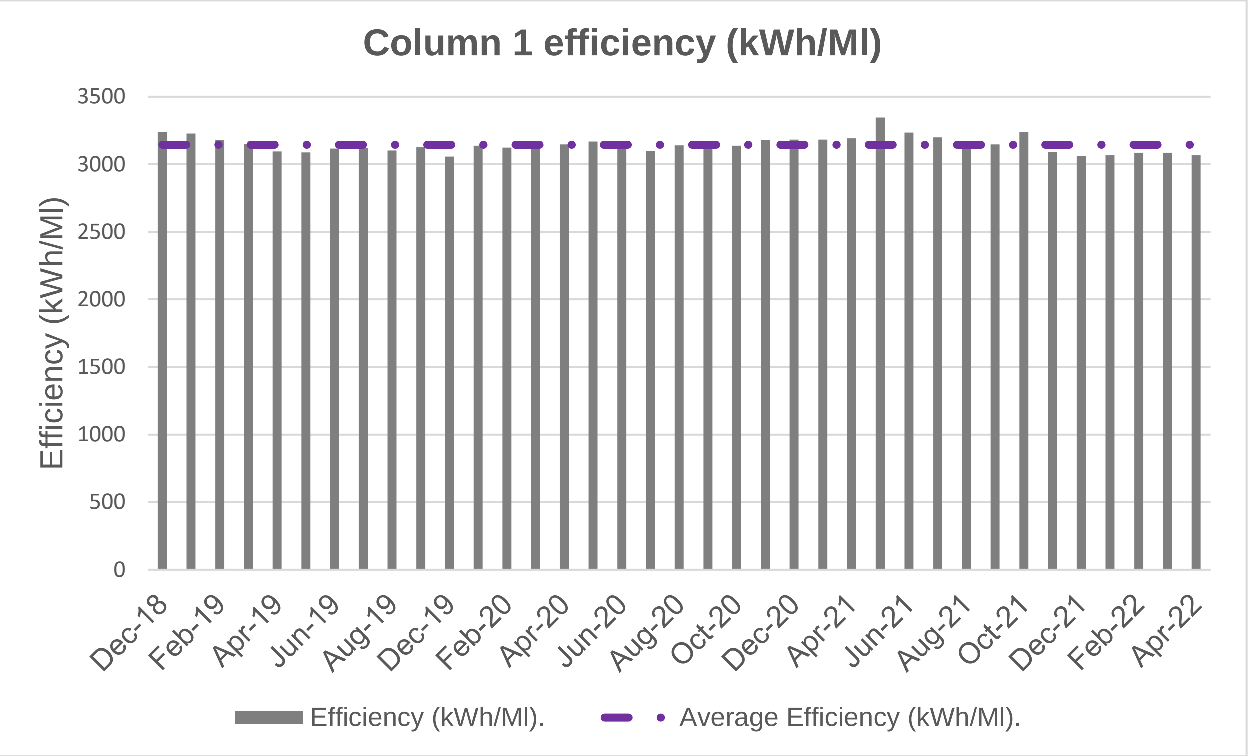

Figure 4-16: Column 1 efficiency (kWh/Ml)

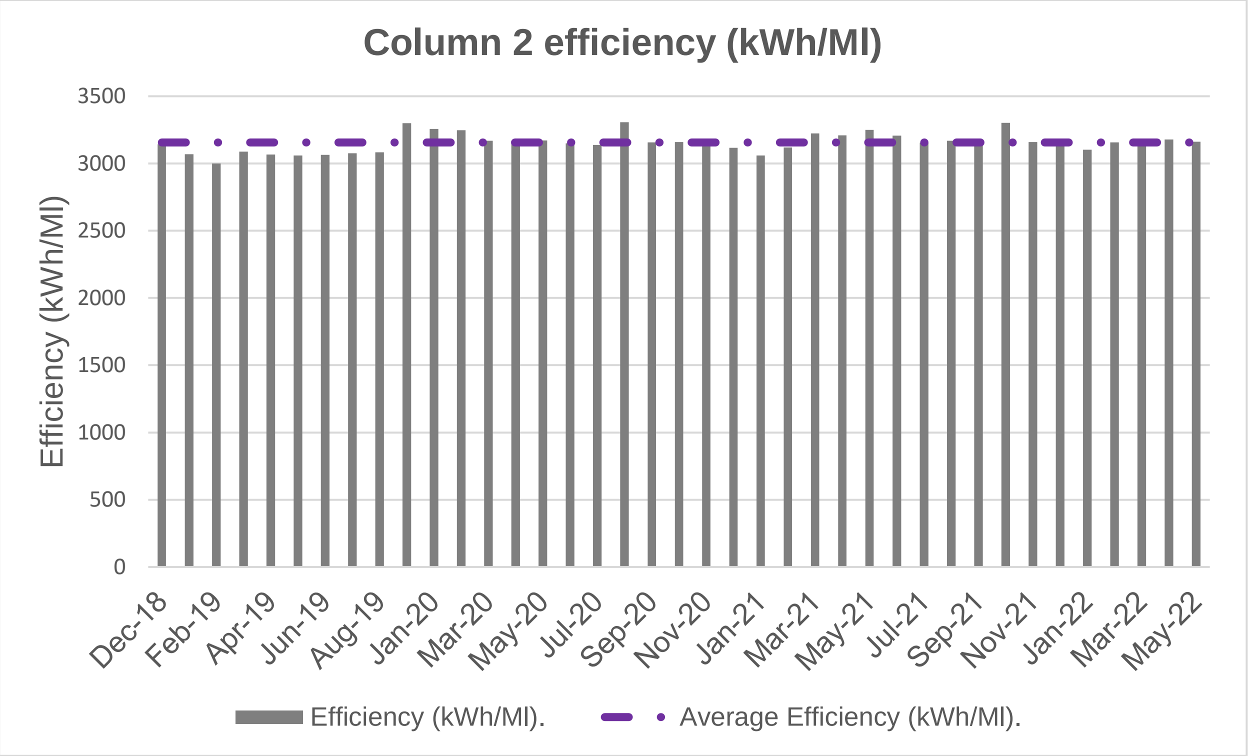

Figure 4-17: Column 2 efficiency (kWh/Ml)

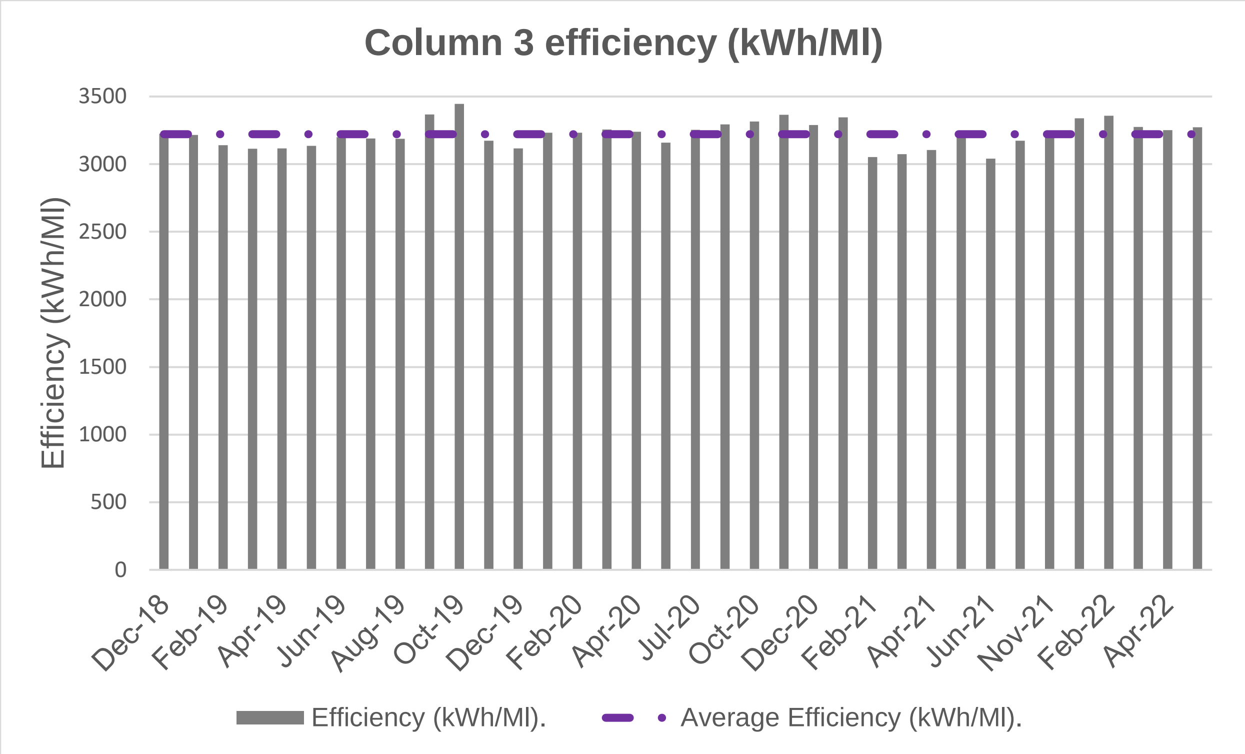

Figure 4-18: Column 3 efficiency (kWh/Ml)

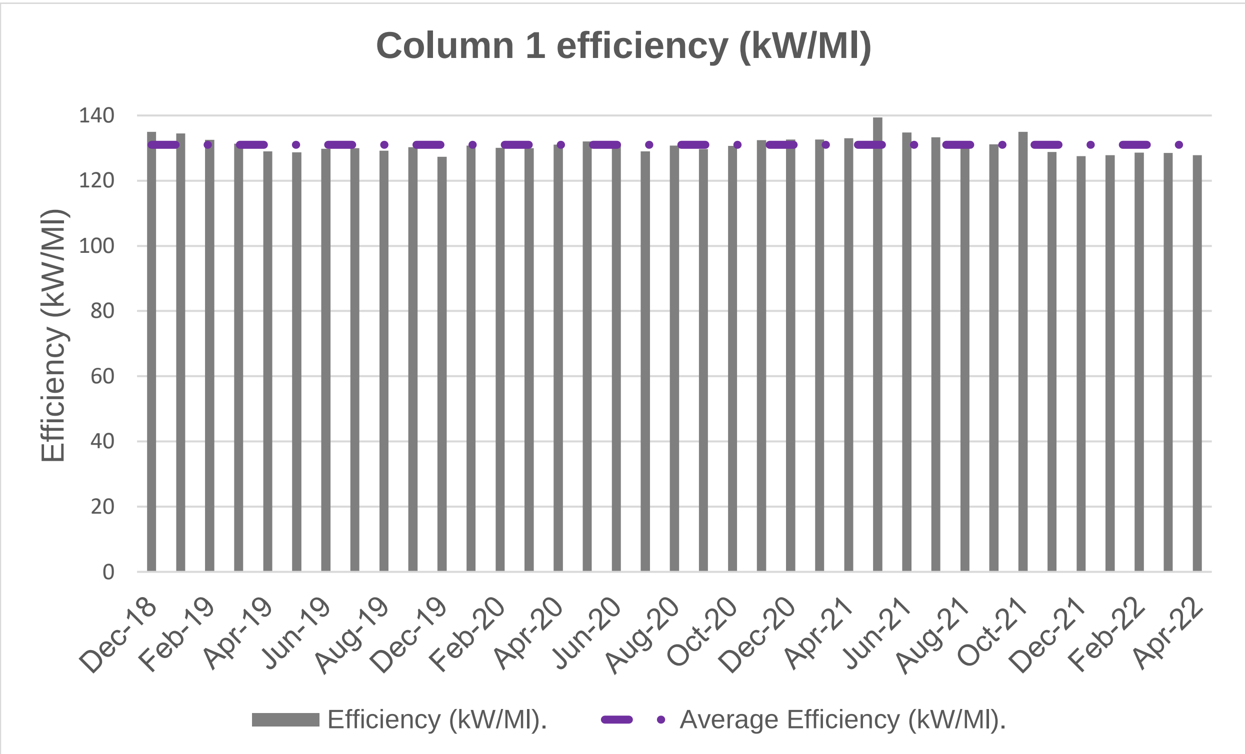

Figure 4-19: Column 1 efficiency (kW/Ml)

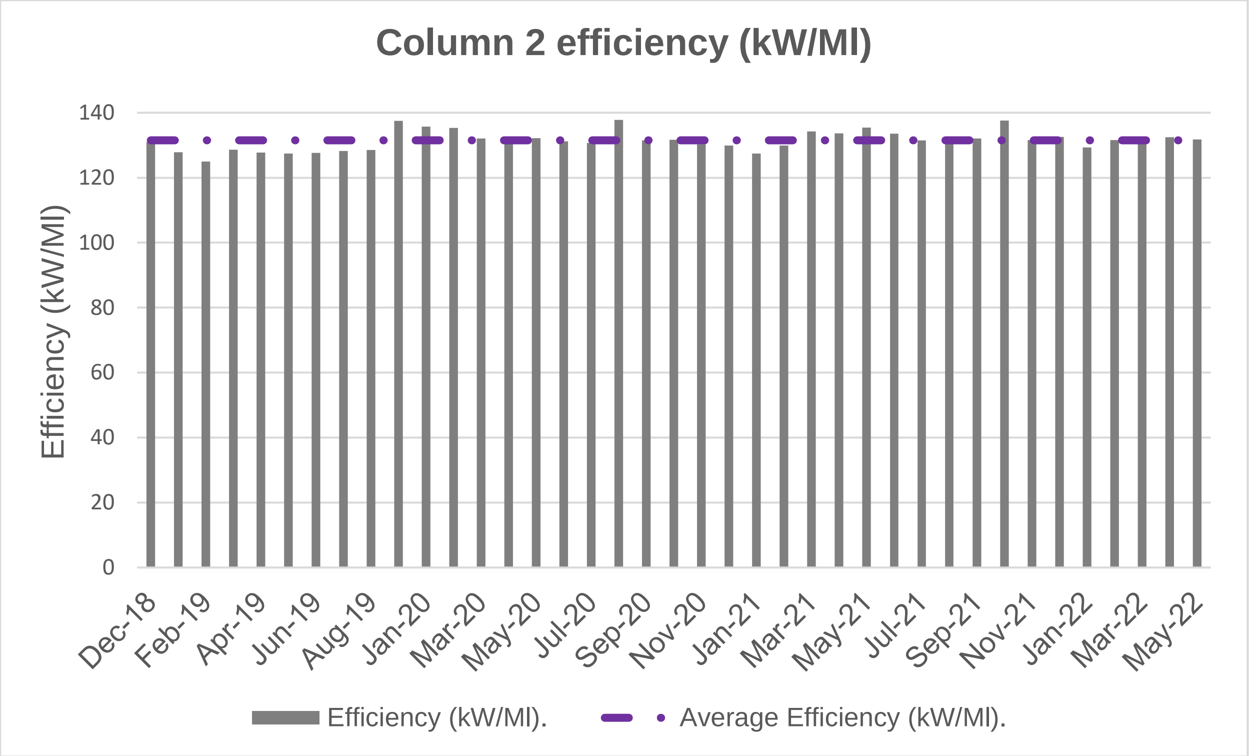

Figure 4-20: Column 2 efficiency (kW/Ml)

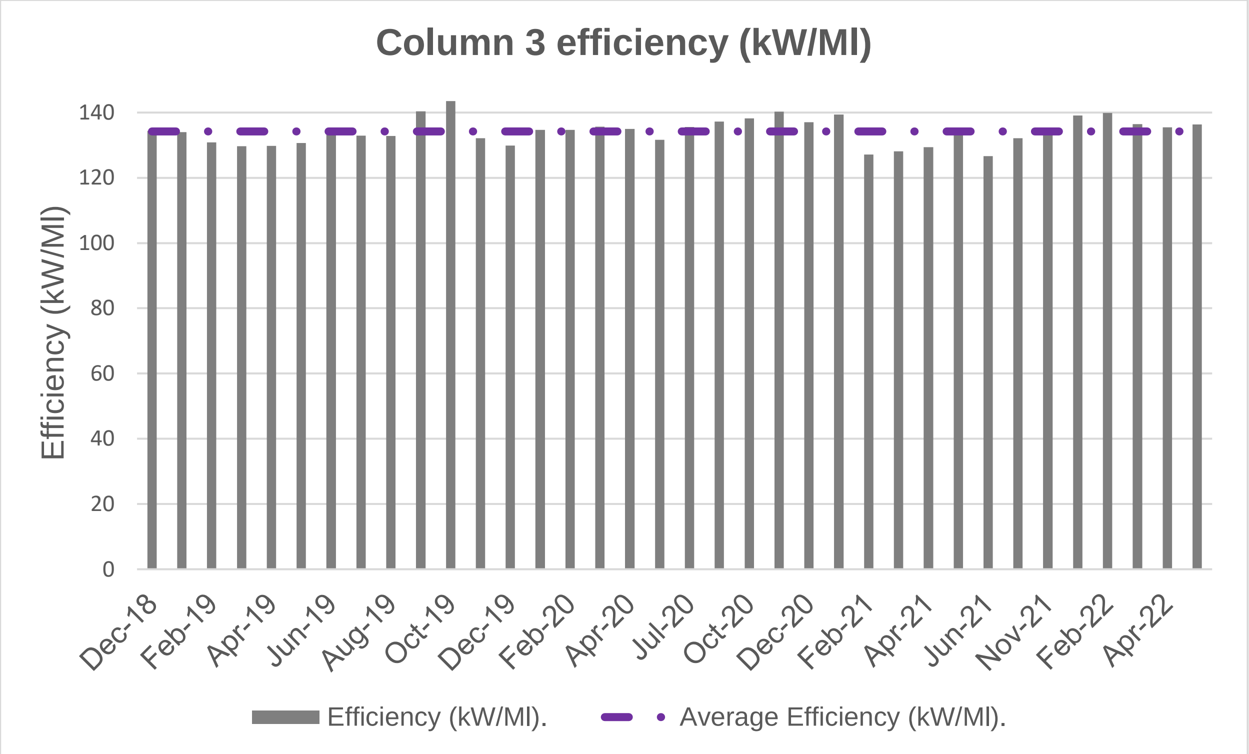

Figure 4-21: Column 3 efficiency (kW/Ml)

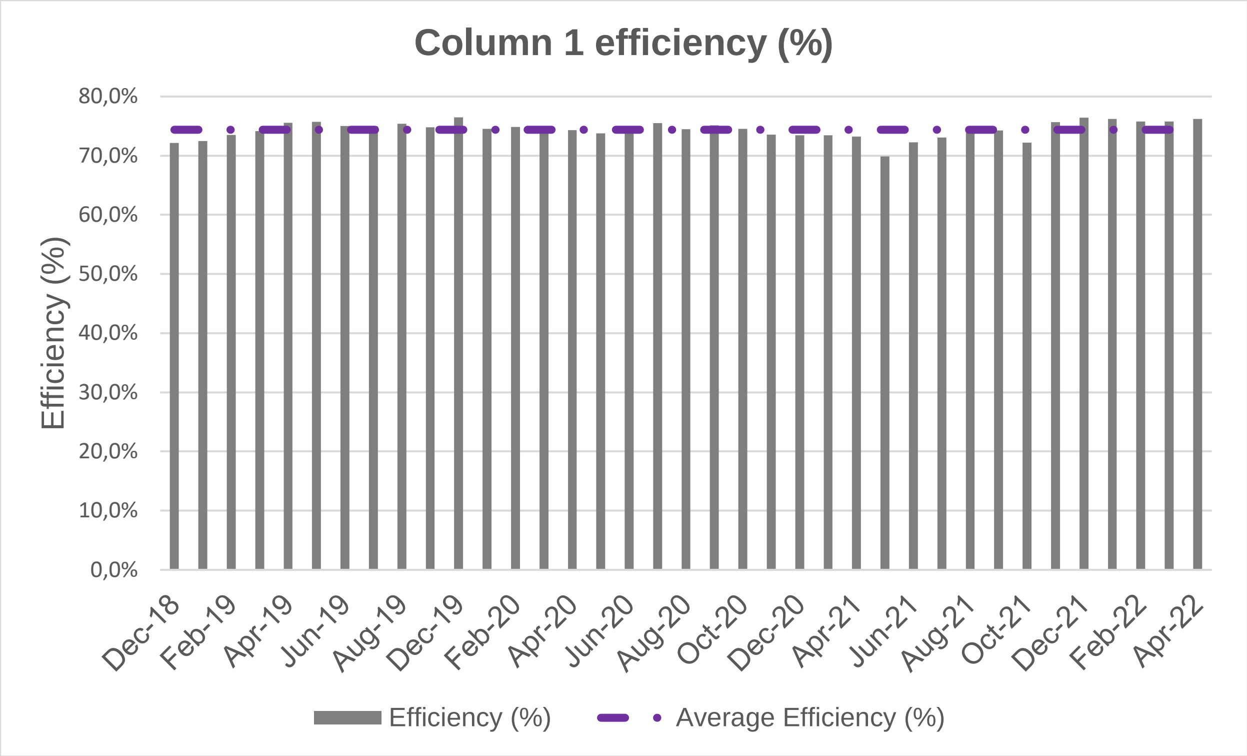

Figure 4-22: Column 1 efficiency (%)

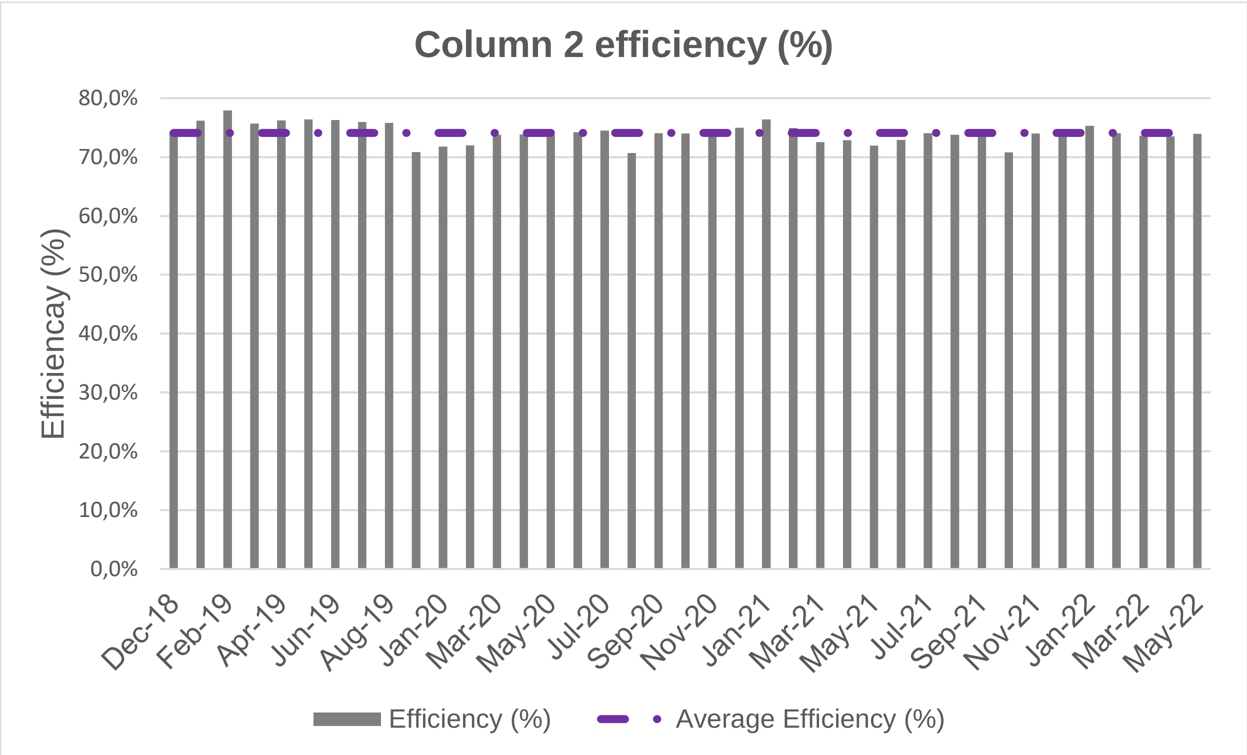

Figure 4-23: Column 2 efficiency (%)

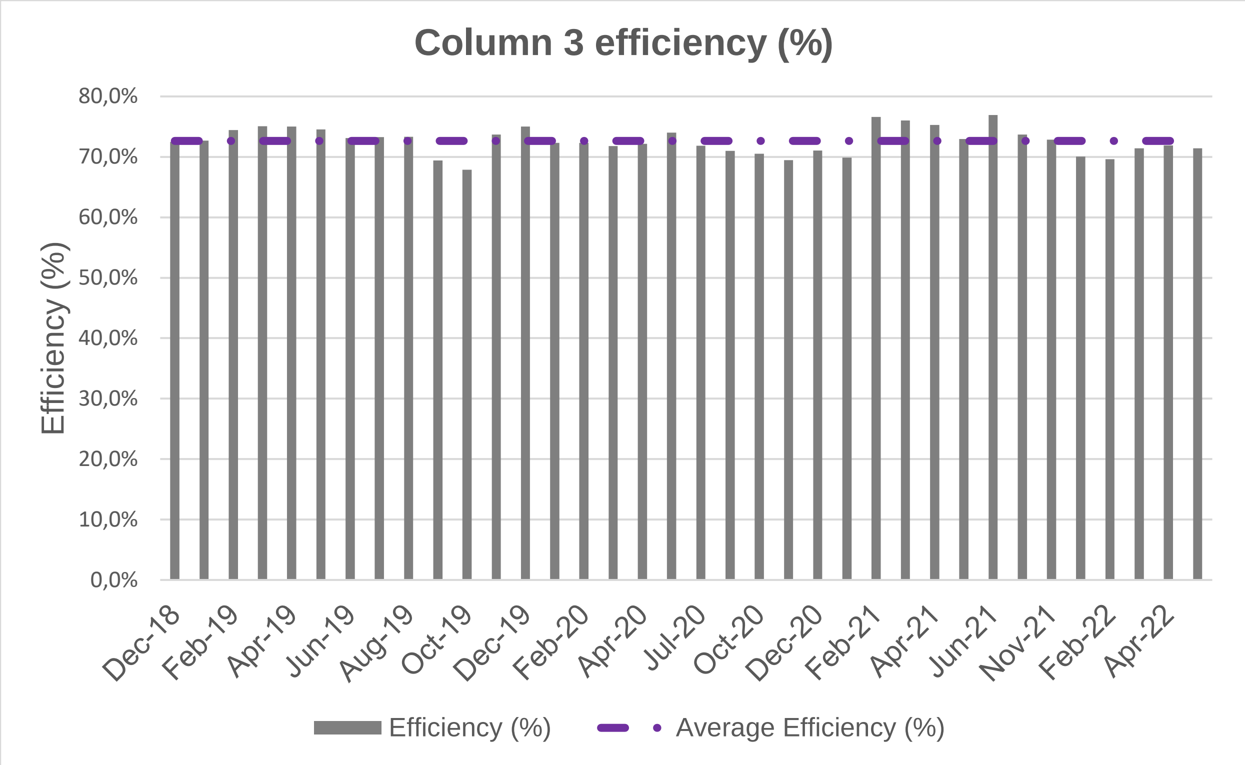

Figure 4-24: Column 3 efficiency (%)

4.2.2.4 Pump column baseline cost

Each pump column's baseline cost was calculated by multiplying the energy tariff with the energy consumed by the pump column. Each pump column's baseline cost was also presented as an effective cost per volume of water pumped, to compare different months with each other, regardless of the volume of water pumped during the month, and the number of days in the month. Figure 4-25, Figure 4-26 and Figure 4-27 show the monthly cost of columns 1,2 and 3 respectively, as well as the average monthly cost per year. Figure 4-28, Figure 4-29 and Figure 4-30 show the effective monthly cost of Rands per megaliter (R/Ml) of water pumped from columns 1, 2 and 3 respectively, as well as the average effective monthly cost per year in R/Ml.

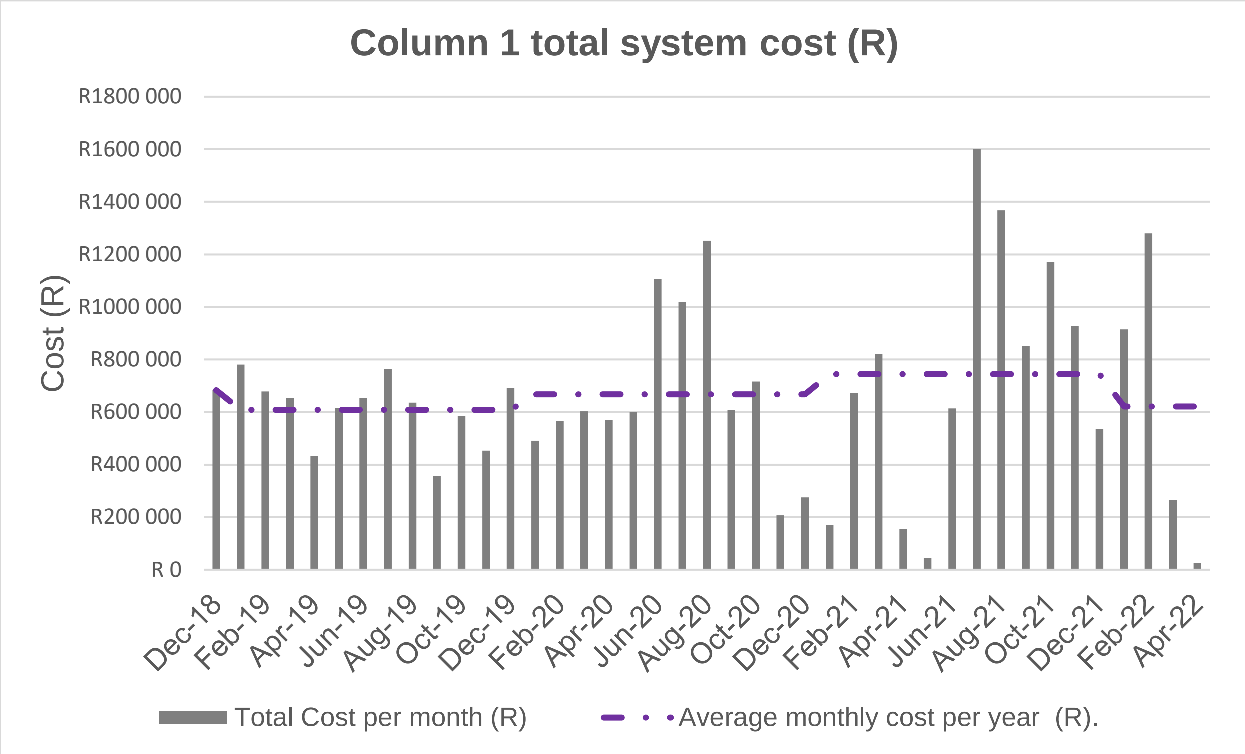

Figure 4-25: Monthly operational cost of column 1

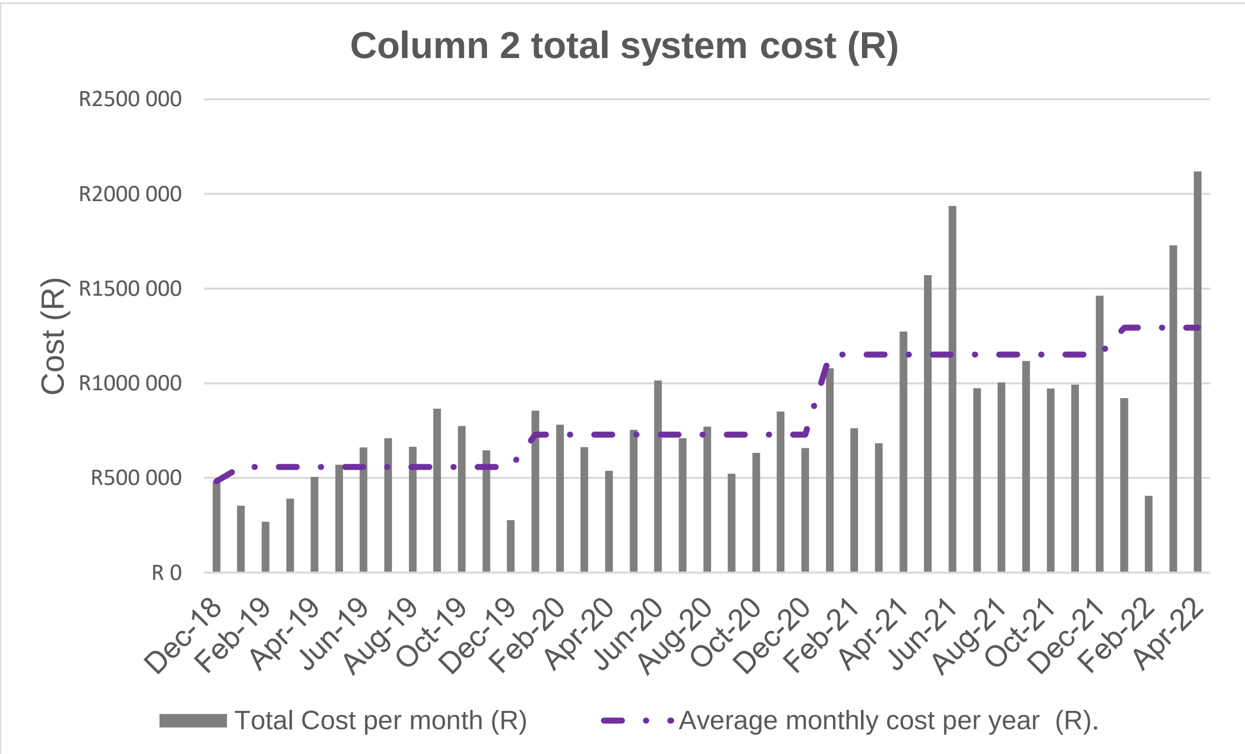

Figure 4-26: Monthly operational cost of column 2

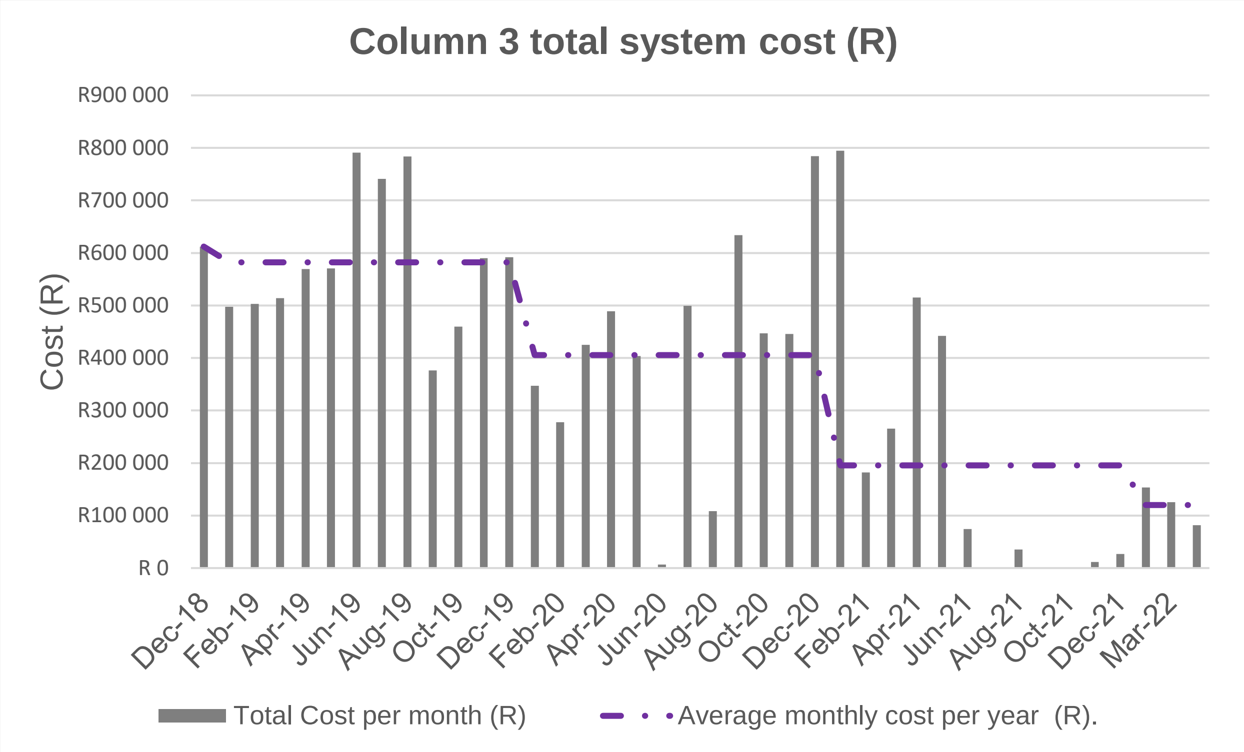

Figure 4-27: Monthly operational cost of column 3

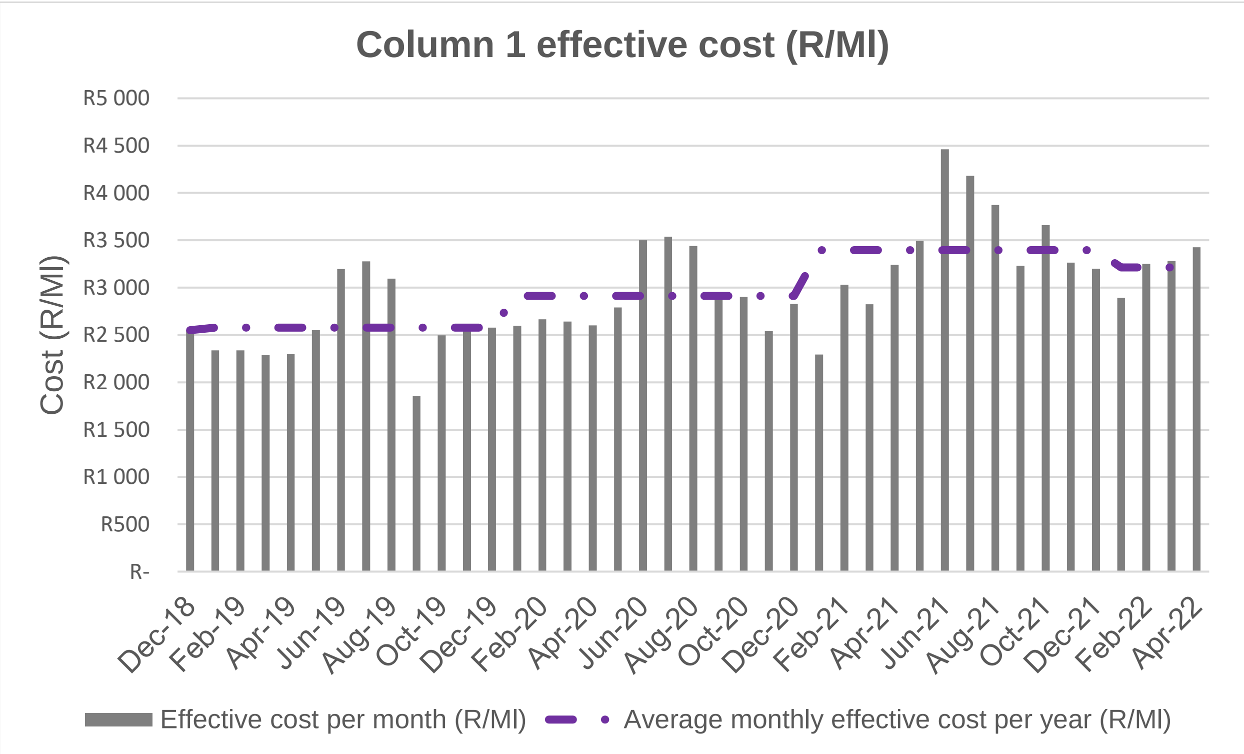

Figure 4-28: Monthly effective cost of column 1 (R/Ml)

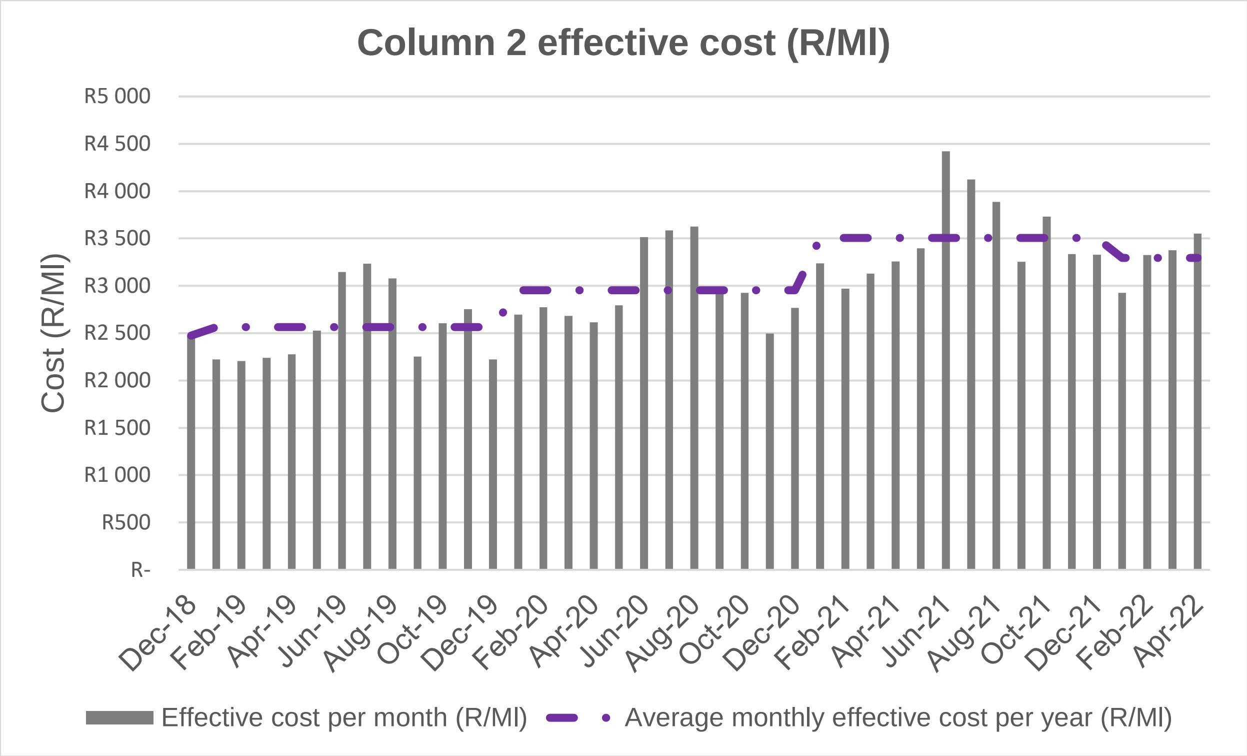

Figure 4-29: Monthly effective cost of column 2 (R/Ml)

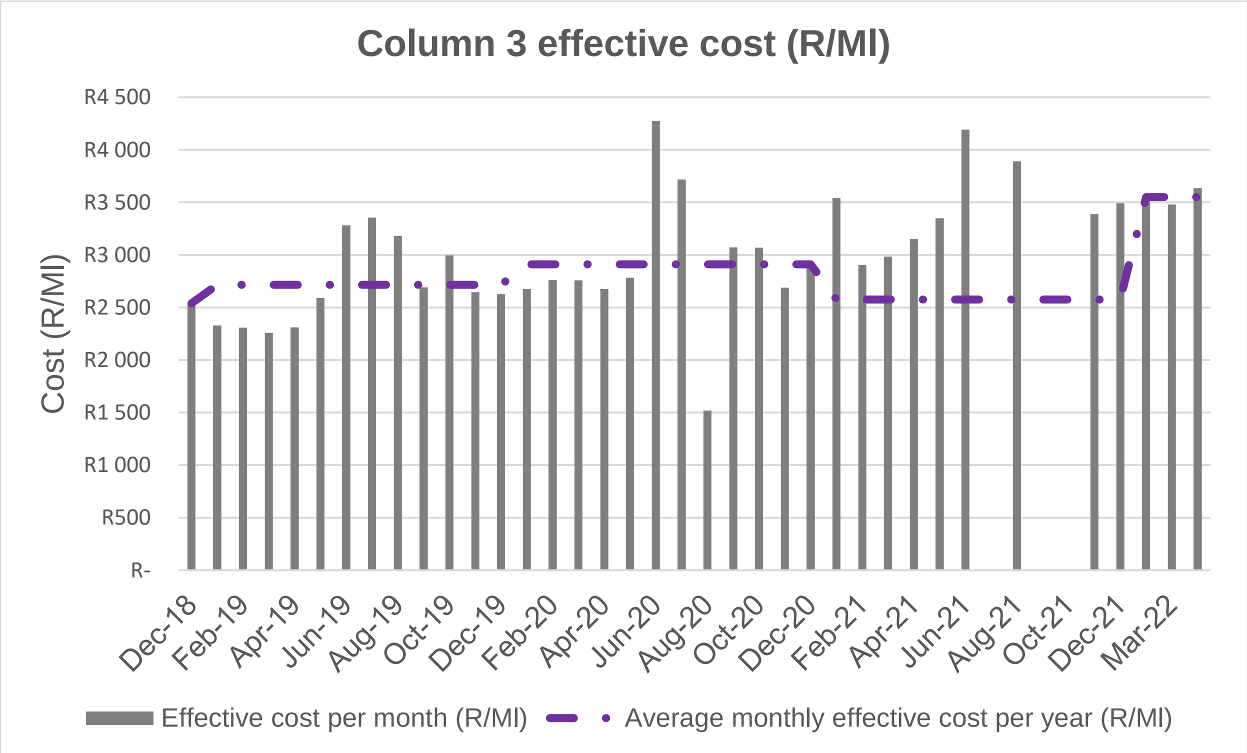

Figure 4-30: Monthly effective cost of column 3 (R/Ml)

4.2.3 Analysis 3: The individual pumps within the pump station

The third analysis was done to give a more detailed breakdown of the individual pumps connected to the three pumping columns. The pump station consists of nine multi-stage pumps, that run at different times to satisfy the operational demand. The pump station consists of three pumping columns (Column 1,2,3). Each pumping column is connected to three pumps, that are run at different times; depending on pump and column availability. Figure 4-9 displays the SCADA view of the pump station, to show the pumping columns connected to the pumps. Column 1 is connected to pumps 1, 2 and 3, column 2 is connected to pumps 4, 5 and 6, and Column 3 is connected to pumps 7, 8 and 9. Various parameters for each pump were calculated to determine the contribution of each pump to the column and the total system performance. The parameters were calculated for each pump to ultimately determine each pump's efficiency as described by equations 2.16 and 2.18. The parameters required to calculate pump efficiency are motor demand, motor efficiency, pump volume flow rate, fluid density and pump head.

4.2.3.1 Motor demand

The demand for each pump was extracted from the power meters as described in section 3.2.8**Error! Reference source not found.**. The demand for each pump is displayed in Table 4-1 below.

Table 4-1: The motor demand of each pump (kW)

Pump column	Pump number	Motor demand (kW)
Column 1	Pump 1	1569
	Pump 2	1624
	Pump 3	1513
Column 2	Pump 4	1828
	Pump 5	1661
	Pump 6	1518
Column 3	Pump 7	1436
	Pump 8	1407
	Pump 9	1636

4.2.3.2 Motor efficiency

The motor efficiency was extracted from the graph displayed in Figure 2-13. The demand for all the motors is well above 1000 kW, which indicates that the efficiency of the motors is constant at 95%. The motor efficiency for all the motors will be considered 95%, as it does not change as described by De Almeida *et al.* (2013:1). The motors installed in the pump station as rated as IE class-2 (high efficiency) motors.

4.2.3.3 Pump volume flow rate

The volume flow rate of the pumps was extracted from the SCADA as described in section 3.2.8. Since there are three pumps per column and only one flowmeter per column, the data was filtered to extract the flow rate data from the flow meters when only a single pump was running in a column. The maximum number of pumps running in the pump station is three pumps (two pumps in a column, and one pump in a second column). Figure 4-31 shows a graphical representation of the typical operations of the pump station. The volume flow rate of the pumps did not change significantly between 2018 and 2022. The volume flow rate of each pump is displayed in Table 4-2.

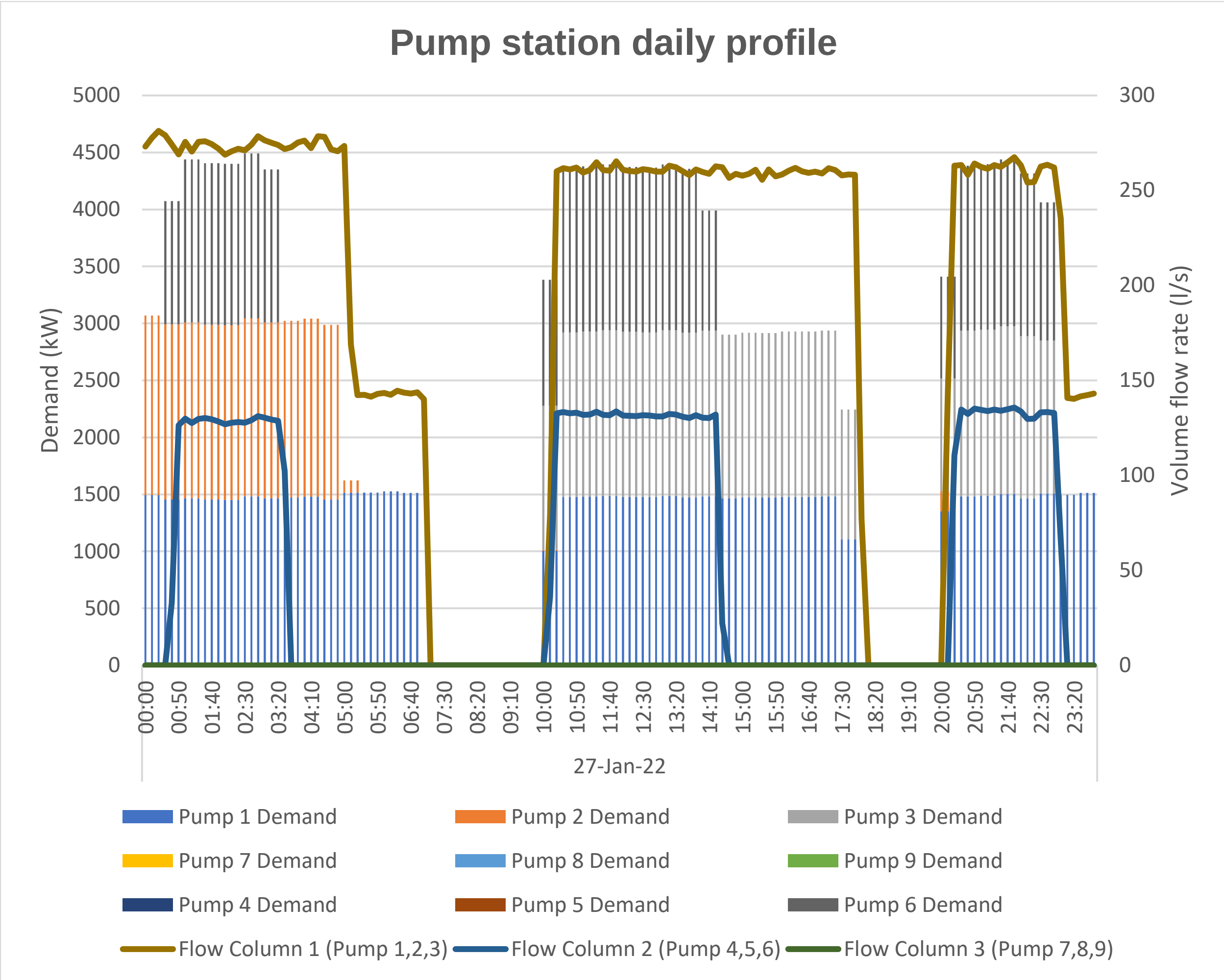

Figure 4-31: The pump station's typical daily profile

Table 4-2: The volume flow rate of each pump (l/s)

Pump column	Pump number	Pump volume flow rate (l/s)
Column 1	Pump 1	142,7
	Pump 2	147,8
	Pump 3	134,4
Column 2	Pump 4	154,8
	Pump 5	152,1
	Pump 6	136,9
Column 3	Pump 7	124,4
	Pump 8	113,5
	Pump 9	154,4

4.2.3.4 Pump head

The pump head was determined by extracting the data from the pressure transmitters installed on each pump. The suction and discharge pressure on each pump was constant, because the water supplied to the pumps came from the same dam at a fixed level, and the pumps discharged at the same fixed level into the same dam. The differential pressure over each pump was measured as 7995 kPa.

4.2.3.5 Pump efficiency

Each pump's efficiency was calculated to determine each pump's performance. Each pump's efficiency was calculated with three methods. The first was the kWh/Ml as described by Yates and Weybourne (2001:105). The second method is similar to the first method. The kWh/Ml was converted to a kW/Ml value. The last method was to calculate the pump efficiency with equations 2.16 and 2.18 as described by Stoffel (2015:11). Each pump's efficiency in terms of kWh/Ml, kW/Ml and percentage (%) is displayed in Table 4-3. The efficiencies in terms of kWh/Ml, kW/Ml and percentage (%) are also displayed graphically in Figure 4-32, Figure 4-33 and Figure 4-34 respectively.

Table 4-3: Individual pump efficiency

Pump column	Pump number	Efficiency (kWh/Ml)	Efficiency (kW/Ml)	Efficiency (%)
Column 1	Pump 1	3055	127	76,5%
	Pump 2	3053	127	76,6%
	Pump 3	3127	130	74,8%
Column 2	Pump 4	3280	137	71,3%
	Pump 5	3032	126	77,1%
	Pump 6	3080	128	75,9%
Column 3	Pump 7	3207	134	72,9%
	Pump 8	3443	143	67,9%
	Pump 9	2944	123	79,4%

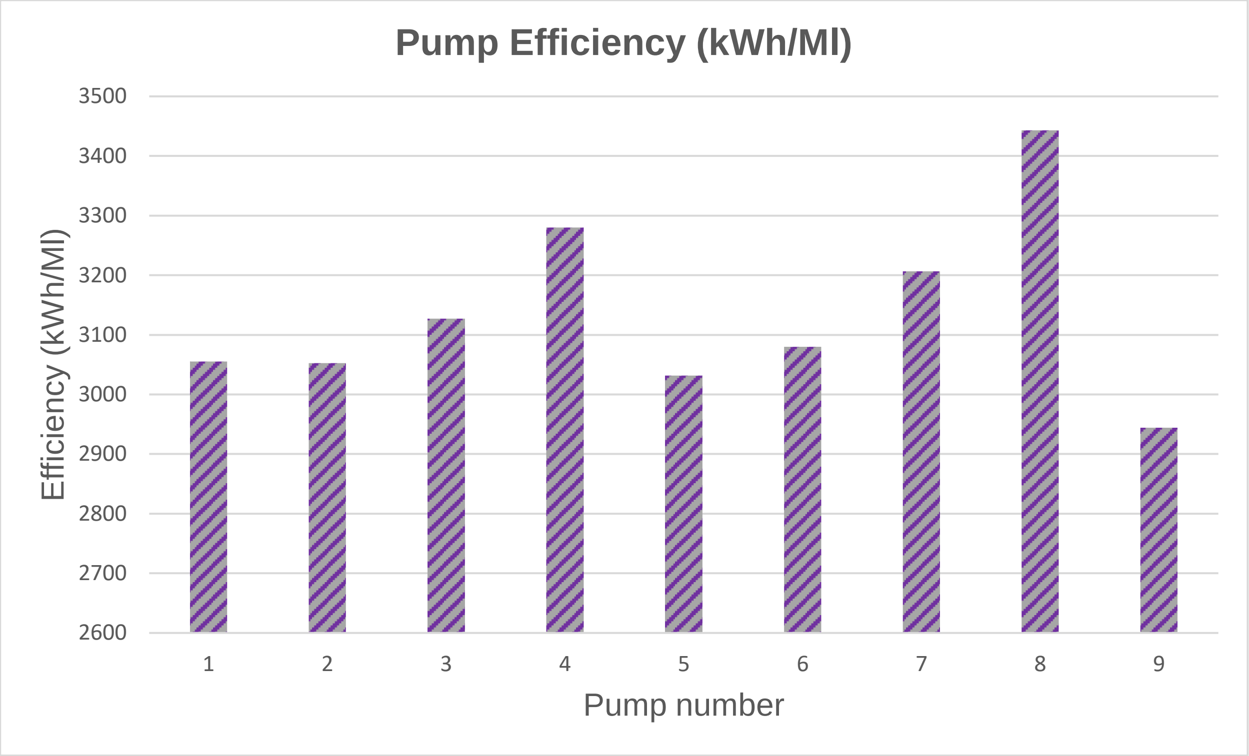

Figure 4-32: Individual pump efficiency (kWh/Ml)

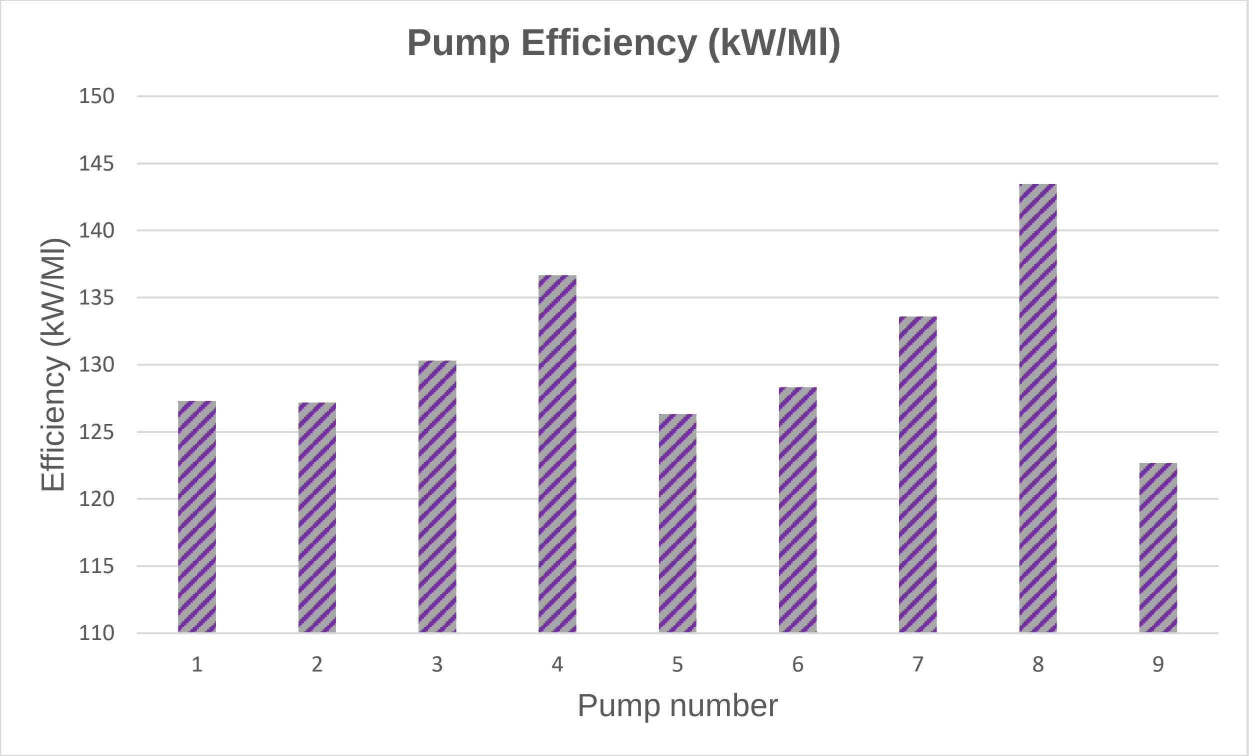

Figure 4-33: Individual pump efficiency (kW/Ml)

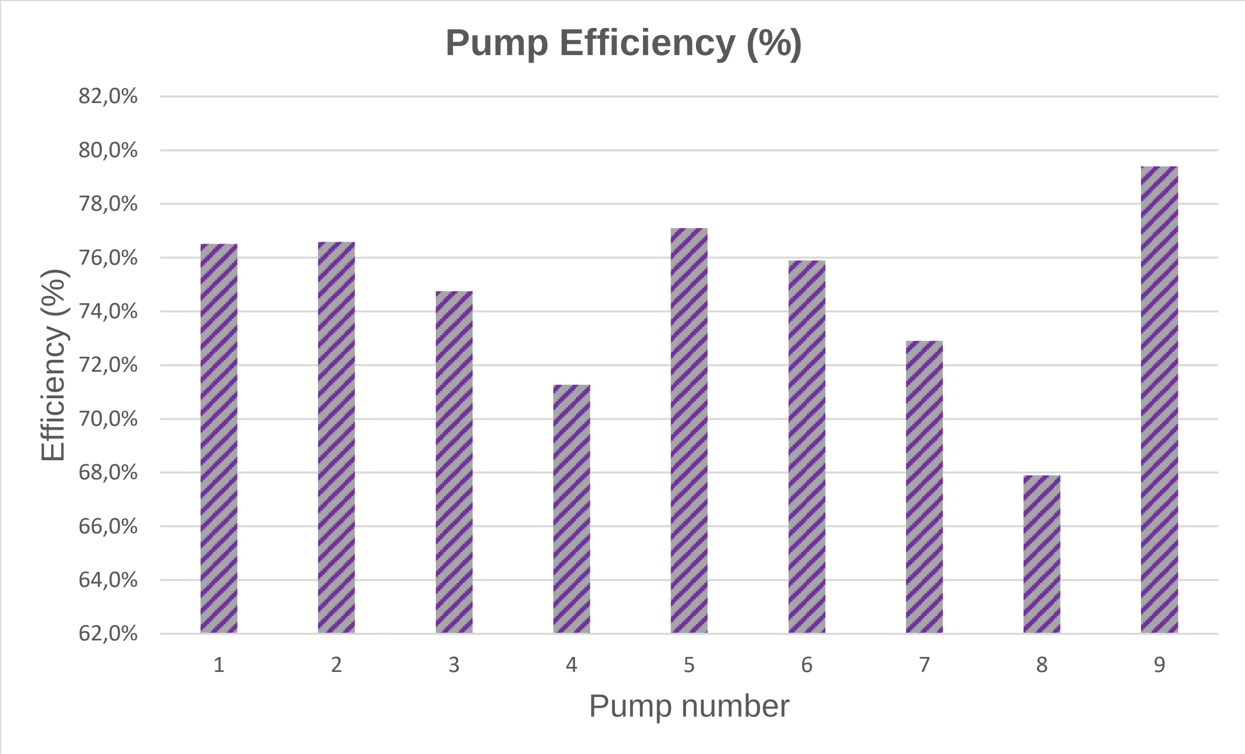

Figure 4-34: Individual pump efficiency (%)

From the analysis, it can be seen that pump 9 is the most efficient. The pump is running at a very high efficiency as shown in Figure 4-35 The operating point of pump 9 is plotted on its pump curve. The head, flow and efficiency match almost exactly, which indicates that the calculation accuracy is high.

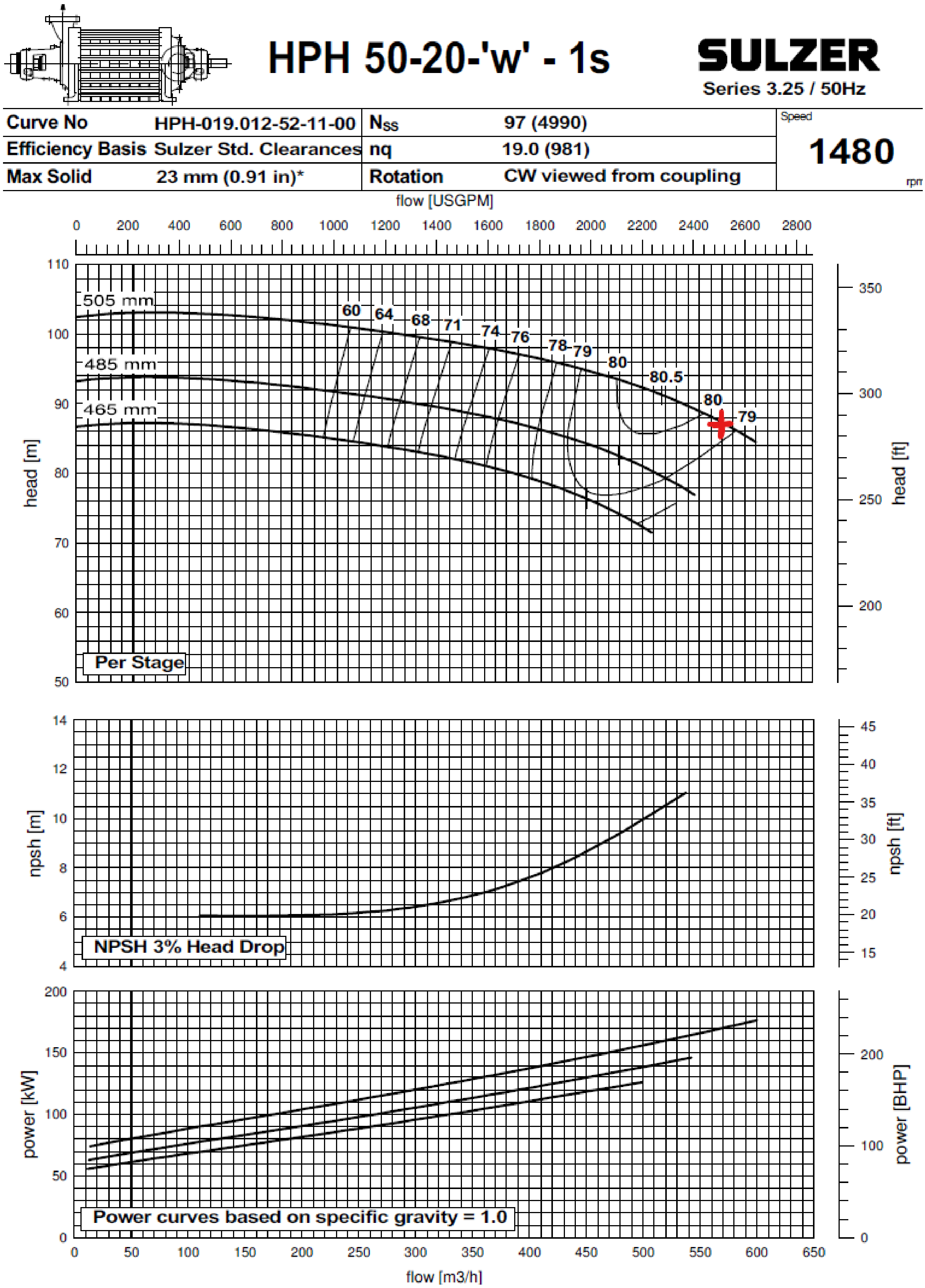

Figure 4-35: Pump 9's performance plotted on its characteristic curve

4.2.3.6 The individual Pump baseline cost

Each pump’s baseline cost was calculated by multiplying the energy tariff by the energy consumed by each pump. Each pump’s baseline cost is presented as an effective cost per volume of water pumped, to compare the different pump’s costs per Ml of water pumped. The average effective cost per year is also presented in Table 4-4 and graphically represented in Figure 4-36 for 2019, 2020 and 2021. The cost is only shown for these three years, as these are the only three years with a complete set of data. 2018 and 2022 do not have full sets of data, which will skew the results.

Table 4-4: Individual pump effective cost (R/Ml)

		Effective cost (R/Ml)		
Pump column	**Pump number**	**2019**	**2020**	**2021**
Column 1	Pump 1	R2 597,09	R2 841,52	R3 360,94
	Pump 2	R2 594,67	R2 838,87	R3 357,80
	Pump 3	R2 658,10	R2 908,27	R3 439,89
Column 2	Pump 4	R2 788,19	R3 050,60	R3 608,24
	Pump 5	R2 577,14	R2 819,69	R3 335,12
	Pump 6	R2 618,09	R2 864,50	R3 388,12
Column 3	Pump 7	R2 725,53	R2 982,05	R3 527,15
	Pump 8	R2 926,55	R3 201,99	R3 787,30
	Pump 9	R2 502,59	R2 738,12	R3 238,64

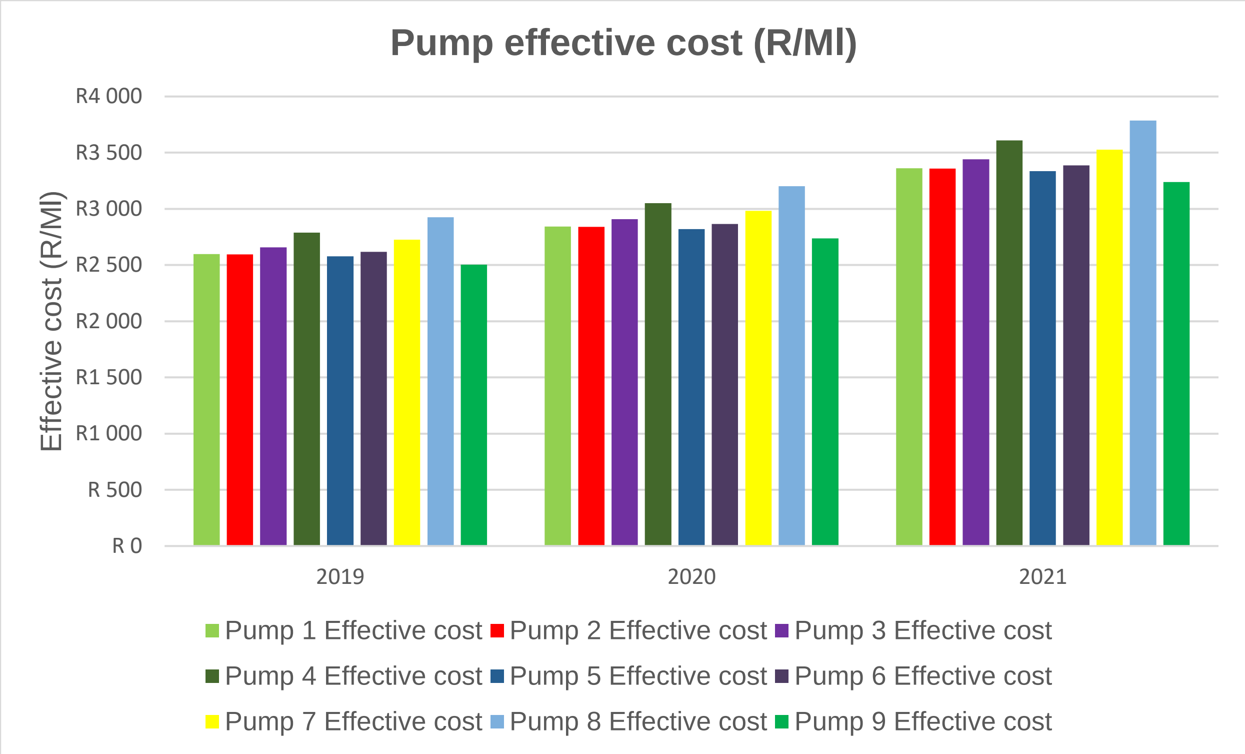

Figure 4-36: Individual pump effective cost (R/Ml)

4.2.4 Analysis 4: Utilisation

From the results of analyses 1,2 and 3, it is clear that the efficiency of the pump station, as well as the efficiencies of the pumping columns, varies from month to month, even though the efficiency's of the pumps remained constant. An analysis was done to determine the utilisation of each pumping column within the pump station, as well as the utilisation of each pump within each pumping column.

4.2.4.1 Pumping column utilisation

The utilisation of each column per month was calculated as the number of hours the column was utilised. Irrespective of the number of pumps running in the column. The number of hours that each column was utilised per month is displayed in Figure 4-37. The utilisation distribution of the columns is displayed in Figure 4-38.

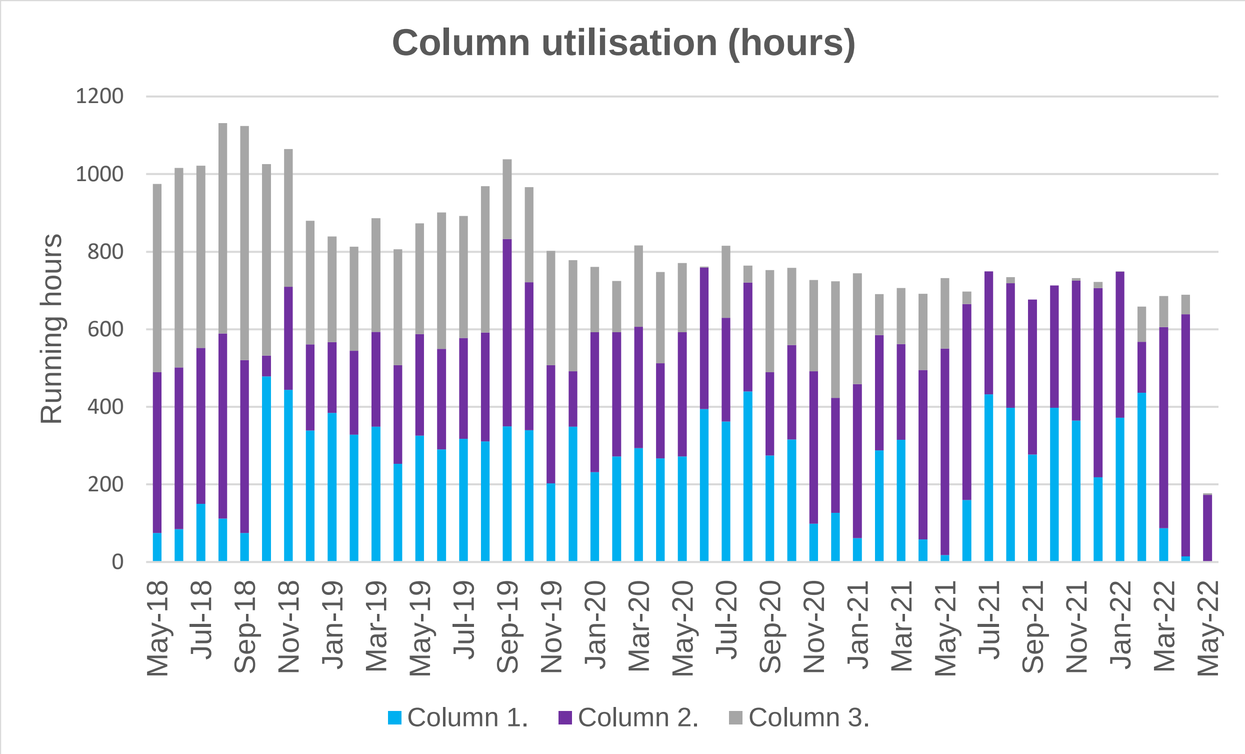

Figure 4-37: Pump column utilisation

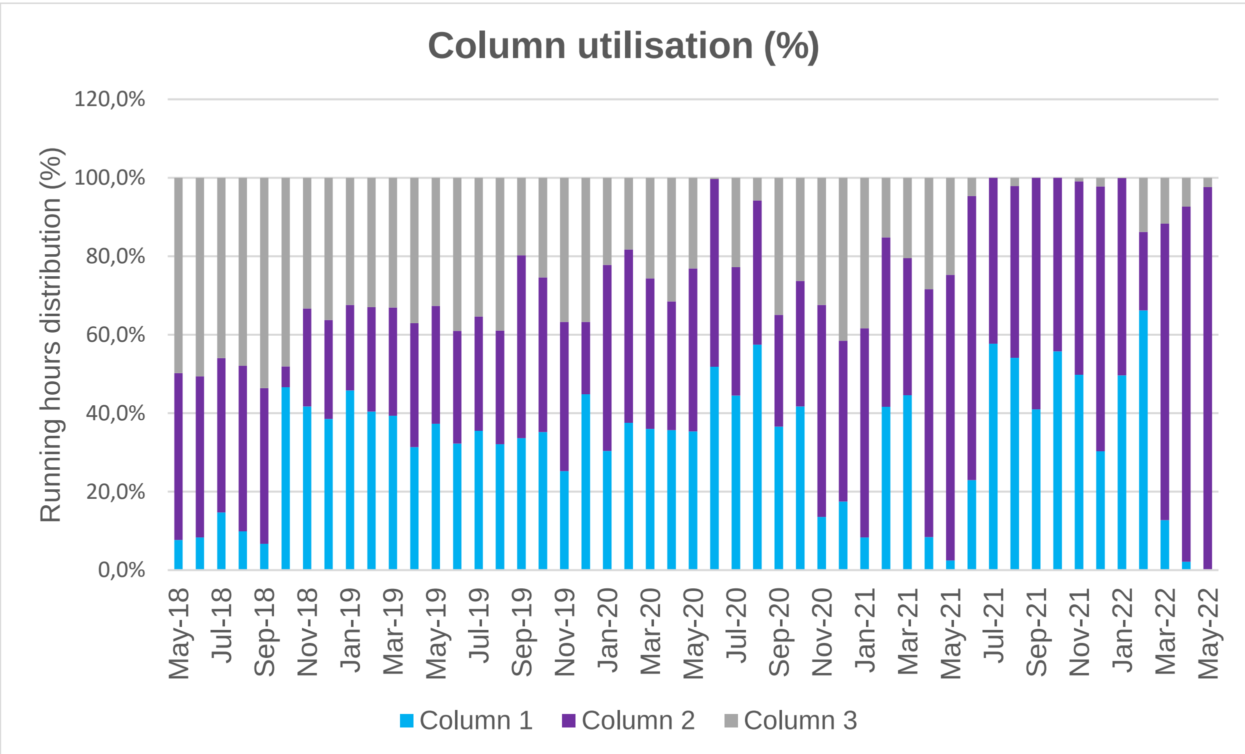

Figure 4-38: Pump column utilisation distribution

4.2.4.2 Pump utilisation within each column

The utilisation of each pump within the three columns per month was calculated as the number of hours the pump was utilised within the column. The number of hours that each pump was utilised within columns 1, 2 and 3 per month is displayed in Figure 4-39, Figure 4-40 and Figure 4-41 respectively. The utilisation distribution of the pumps in columns 1, 2 and 3 is displayed in Figure 4-42, Figure 4-43 and Figure 4-44 respectively.

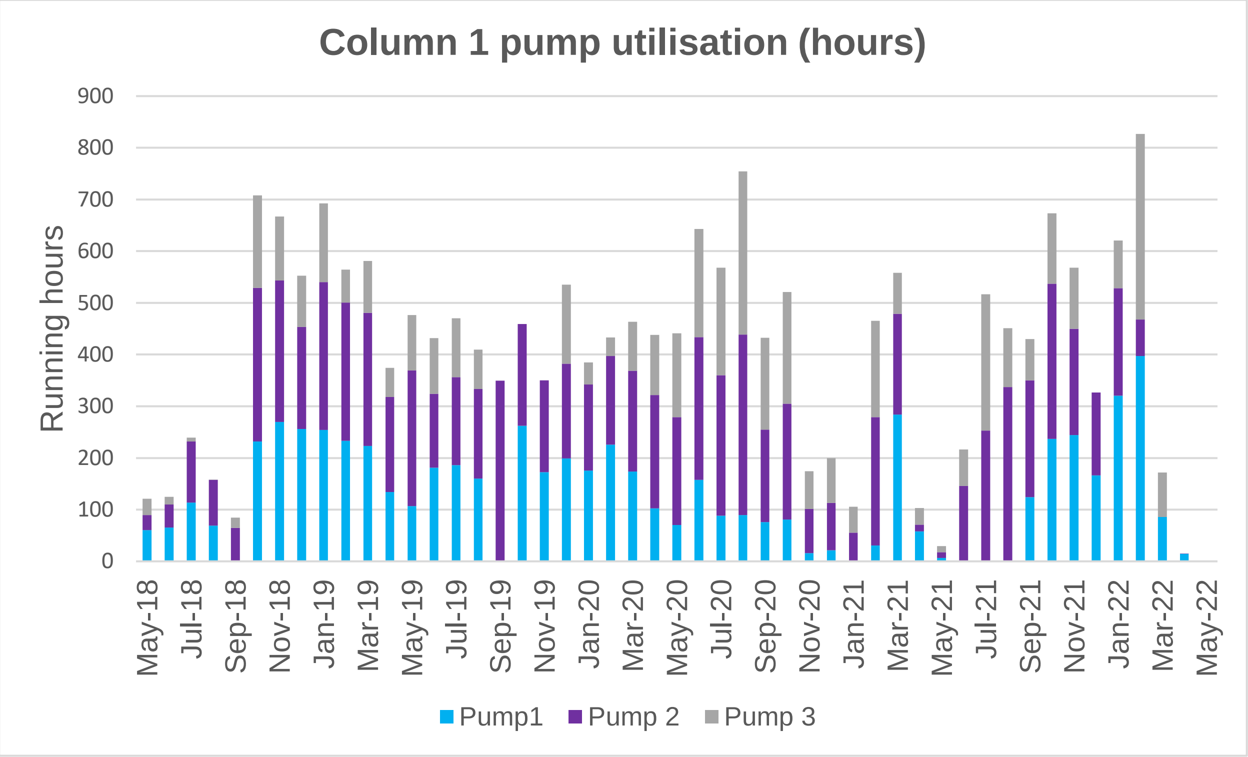

Figure 4-39: Pump running hours (Column 1)

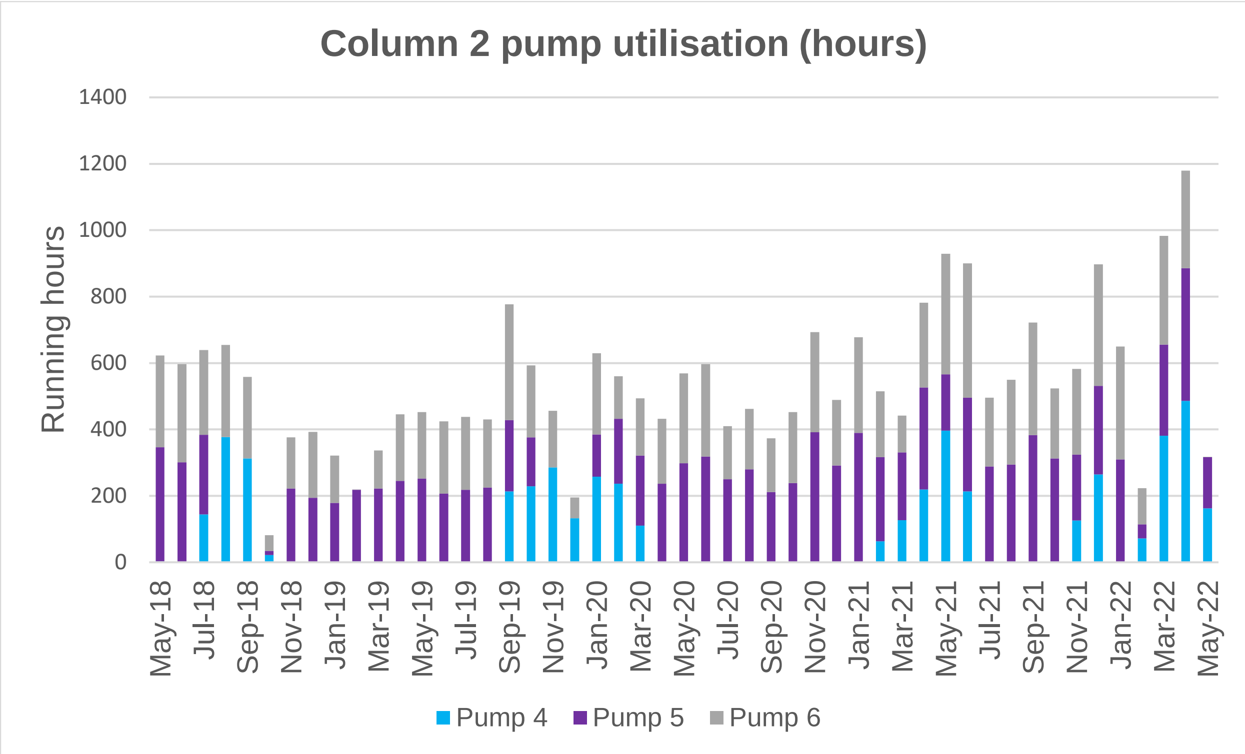

Figure 4-40: Pump running hours (Column 2)

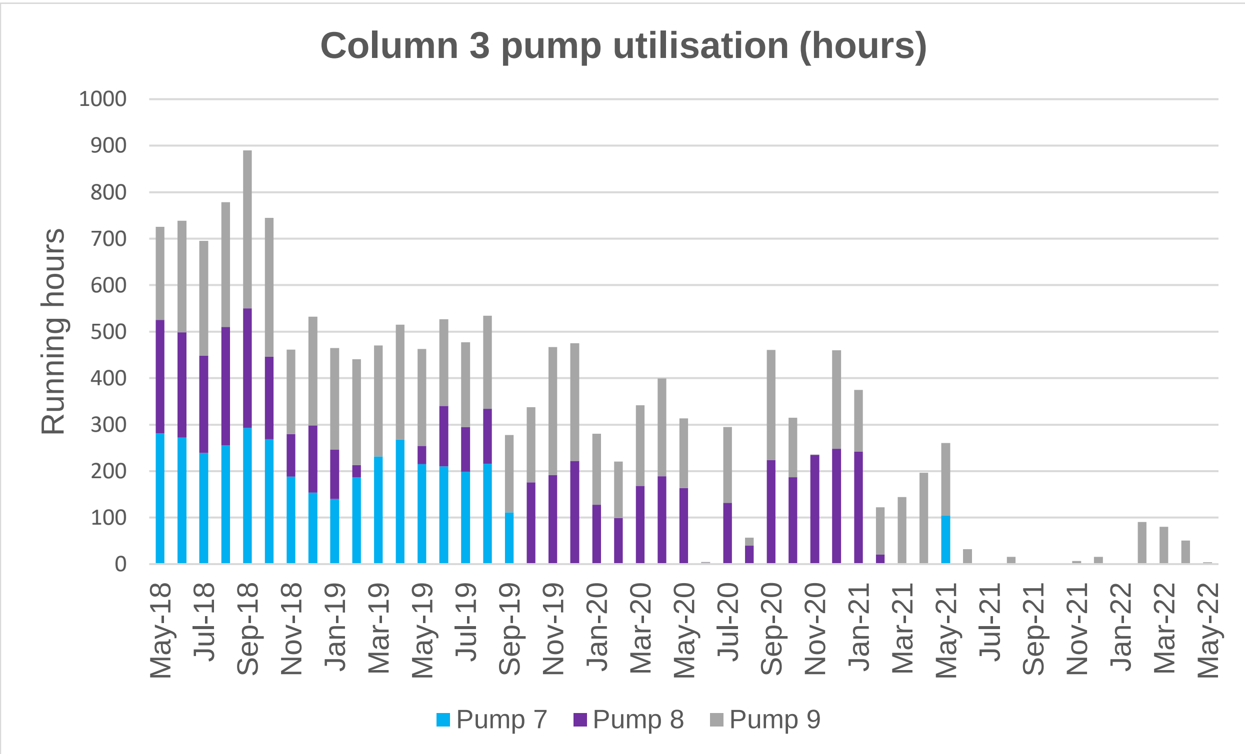

Figure 4-41: Pump running hours (Column 3)

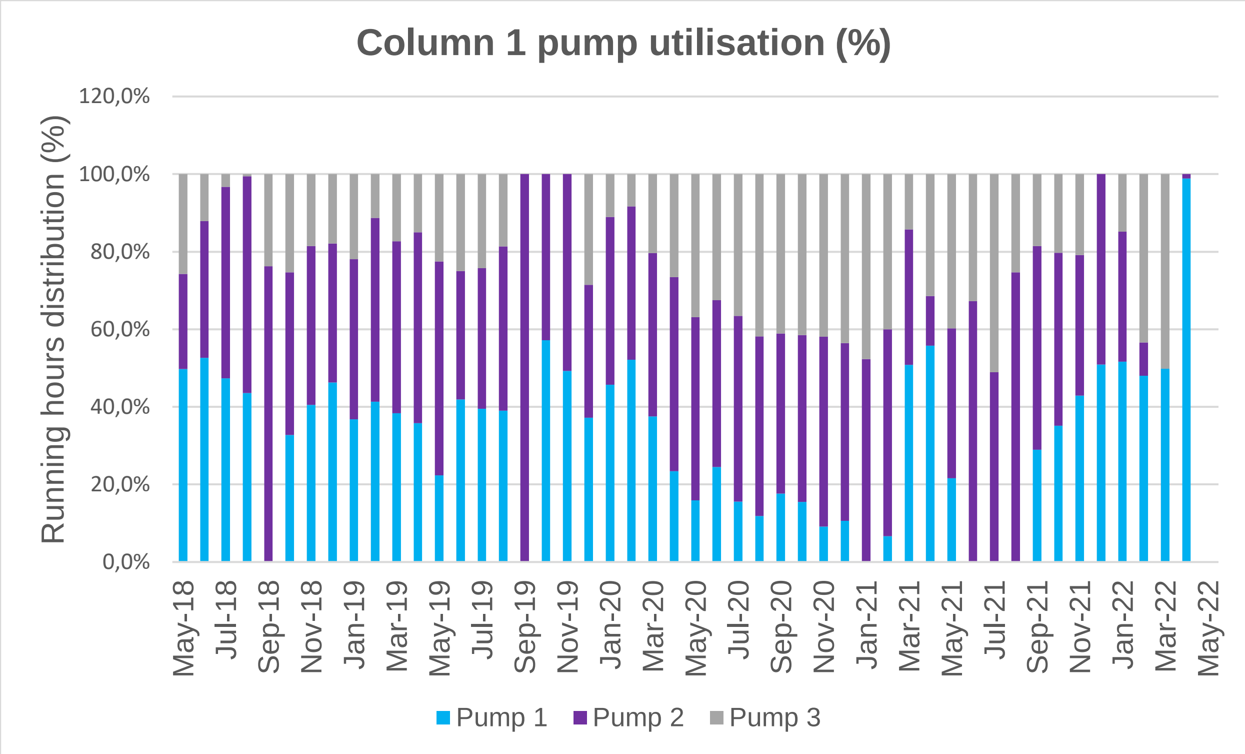

Figure 4-42: Utilisation distribution (Column 1)

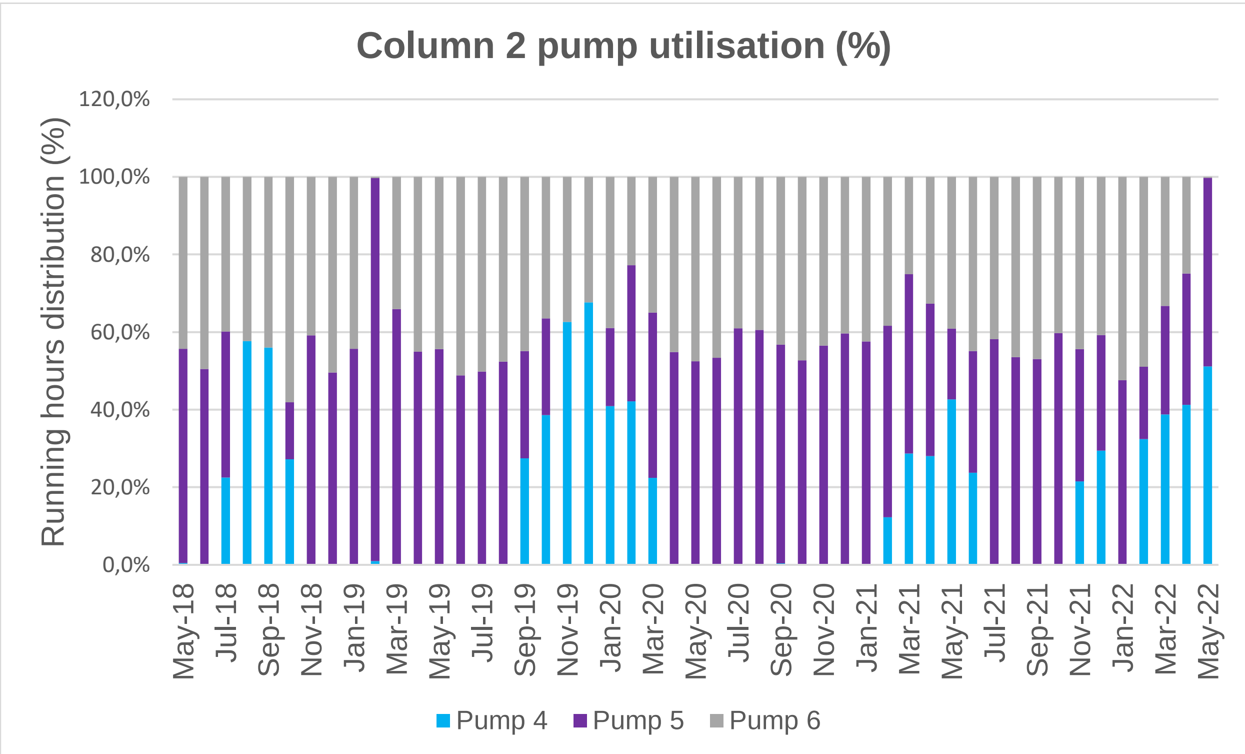

Figure 4-43: Utilisation distribution (Column 2)

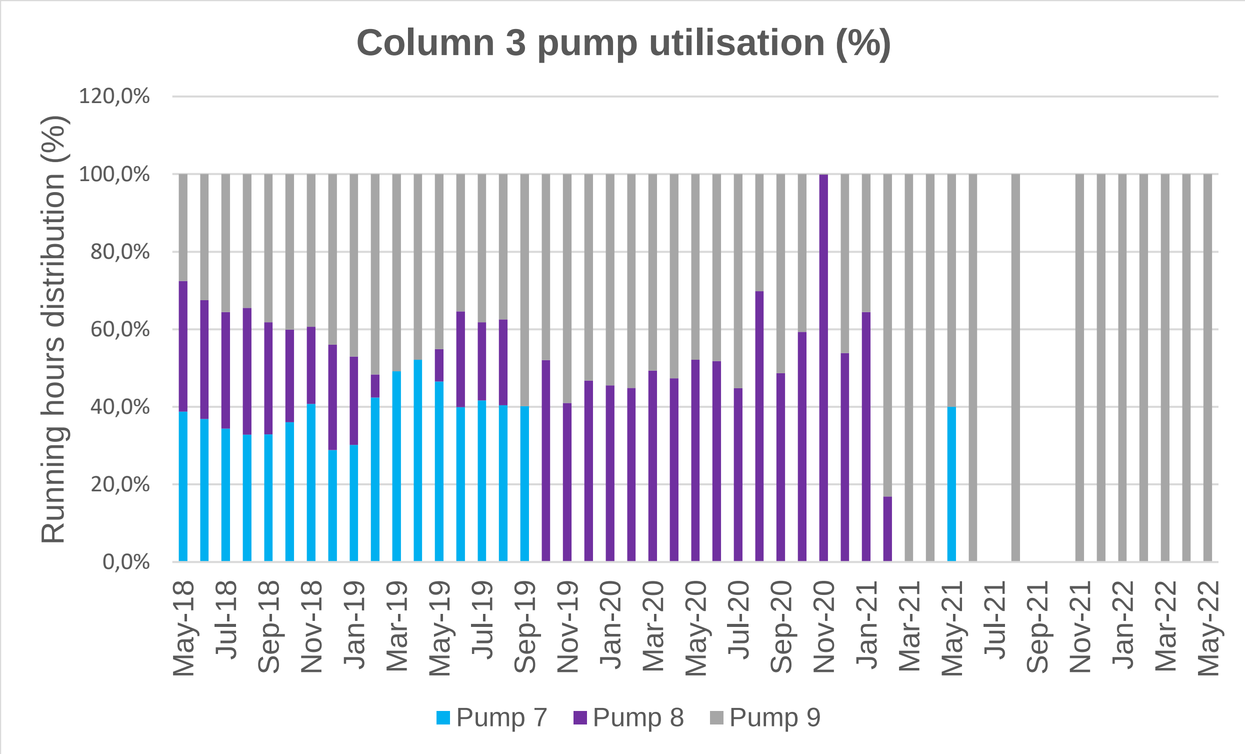

Figure 4-44: Utilisation distribution (Column 3)

4.2.4.3 Pump utilisation within the pump station

The utilisation of each pump within the pump station was calculated. The utilisation distribution of the pumps for 2019, 2020 and 2021 is displayed in Figure 4-45, Figure 4-46 and Figure 4-47 respectively.

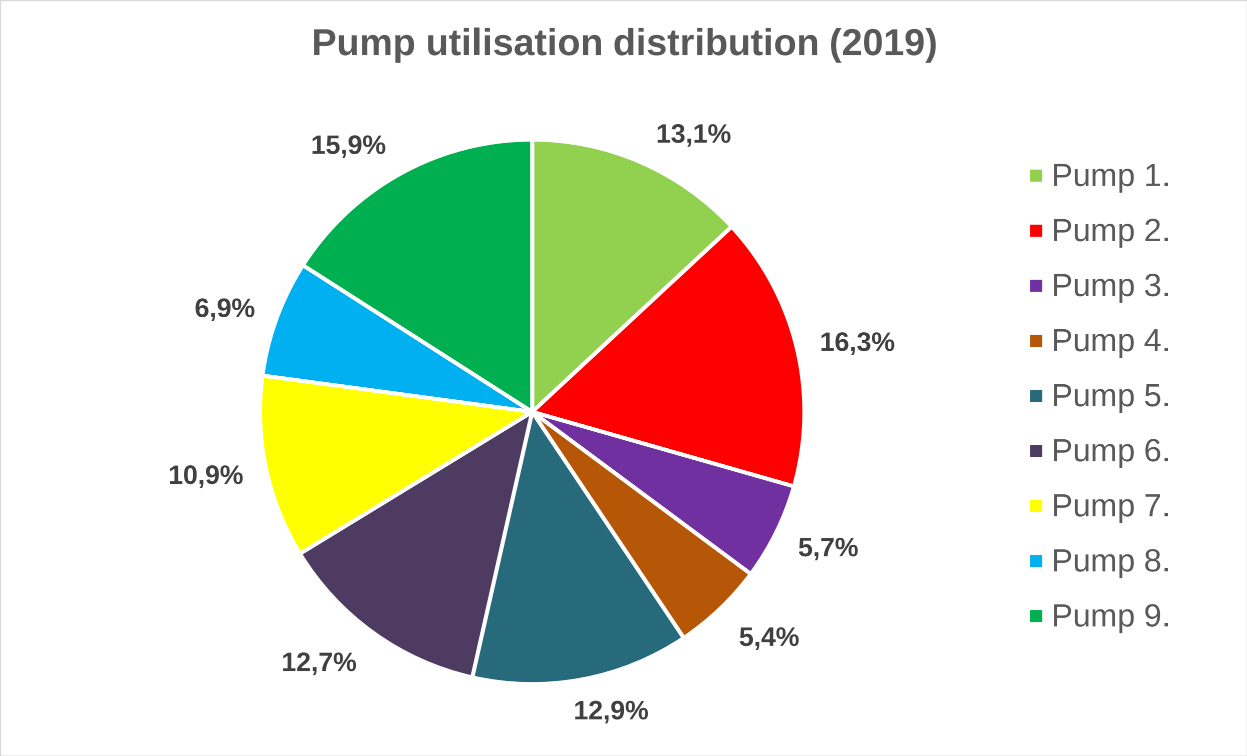

Figure 4-45: Pump utilisation distribution (2019)

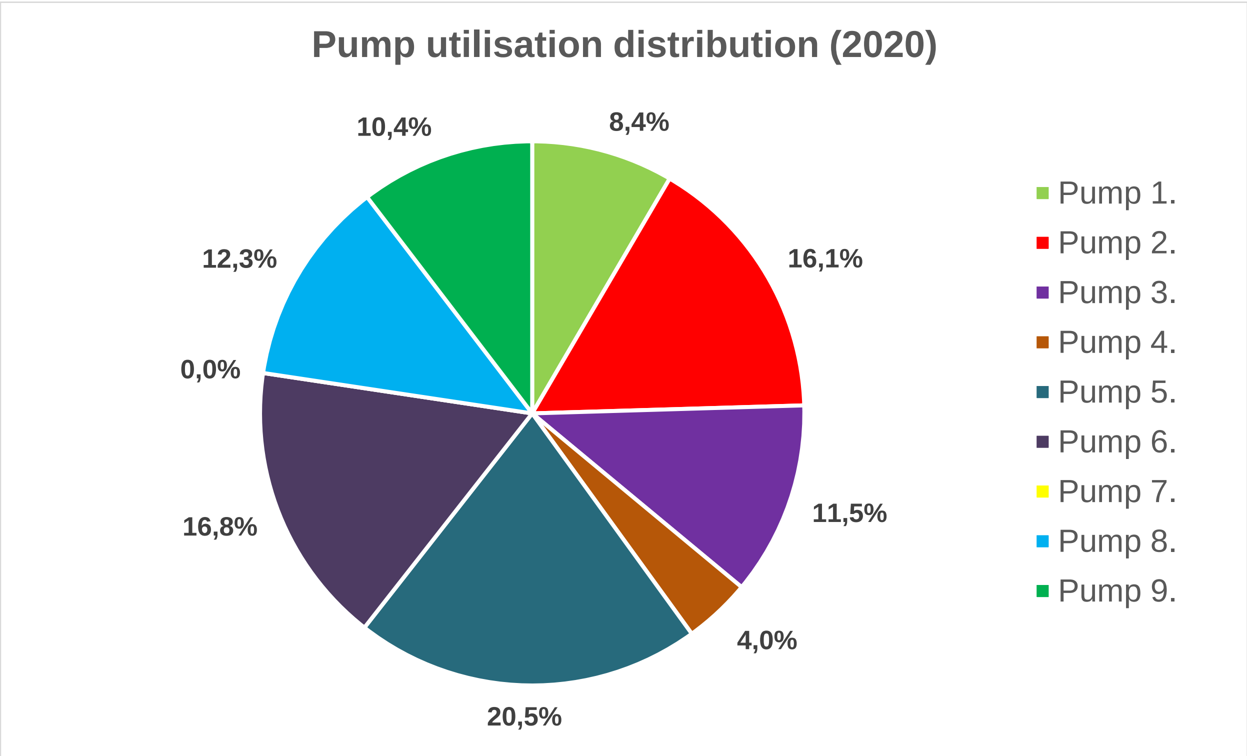

Figure 4-46: Pump utilisation distribution (2020)

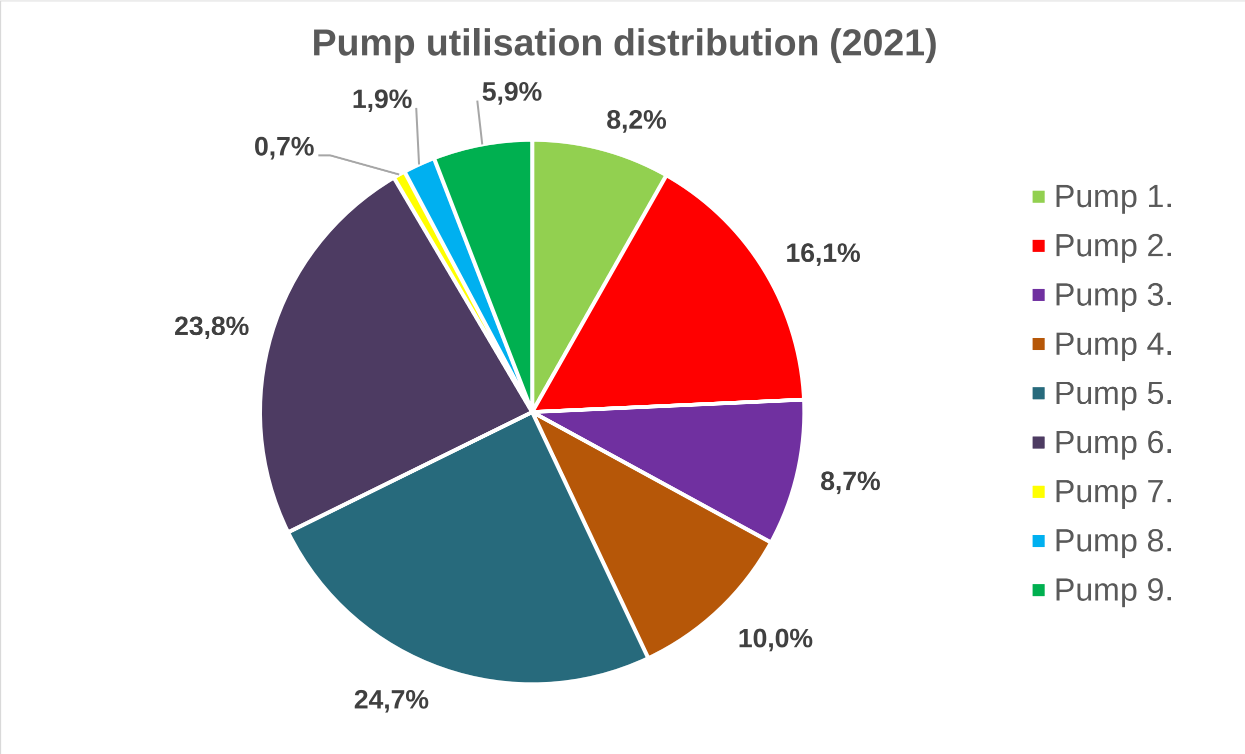

Figure 4-47: Pump utilisation distribution (2021)

4.2.5 Analysis 5: Water pumped per pump

From analyses 1 and 2, it is clear that the efficiency of the pump station and the individual columns vary from month to month, even though the individual pump efficiency stayed constant as described in analyses 3. The varying efficiency is due to the utilisation distribution of the columns and the individual pumps as calculated in analyses 4. Before the financial losses can be determined, the volume of water pumped per pump was calculated, to determine each pump's baseline cost. The volume of water pumped per year by each pump is shown in Table 4-5, as well as graphically represented in Figure 4-48.

Table 4-5: Volume of water pumped by each pump (Ml)

		The volume of water pumped (Ml)		
Pump column	**Pump number**	**2019**	**2020**	**2021**
Column 1	Pump 1	1084,9	656,2	590,7
	Pump 2	1410,7	1296,9	1144,5
	Pump 3	450,3	840,8	553,2
Column 2	Pump 4	481,0	338,0	785,3
	Pump 5	1164,7	1669,8	1834,2
	Pump 6	1035,0	1234,6	1604,5
Column 3	Pump 7	796,6	0,0	46,7
	Pump 8	451,1	741,9	107,2
	Pump 9	1425,8	870,9	445,8

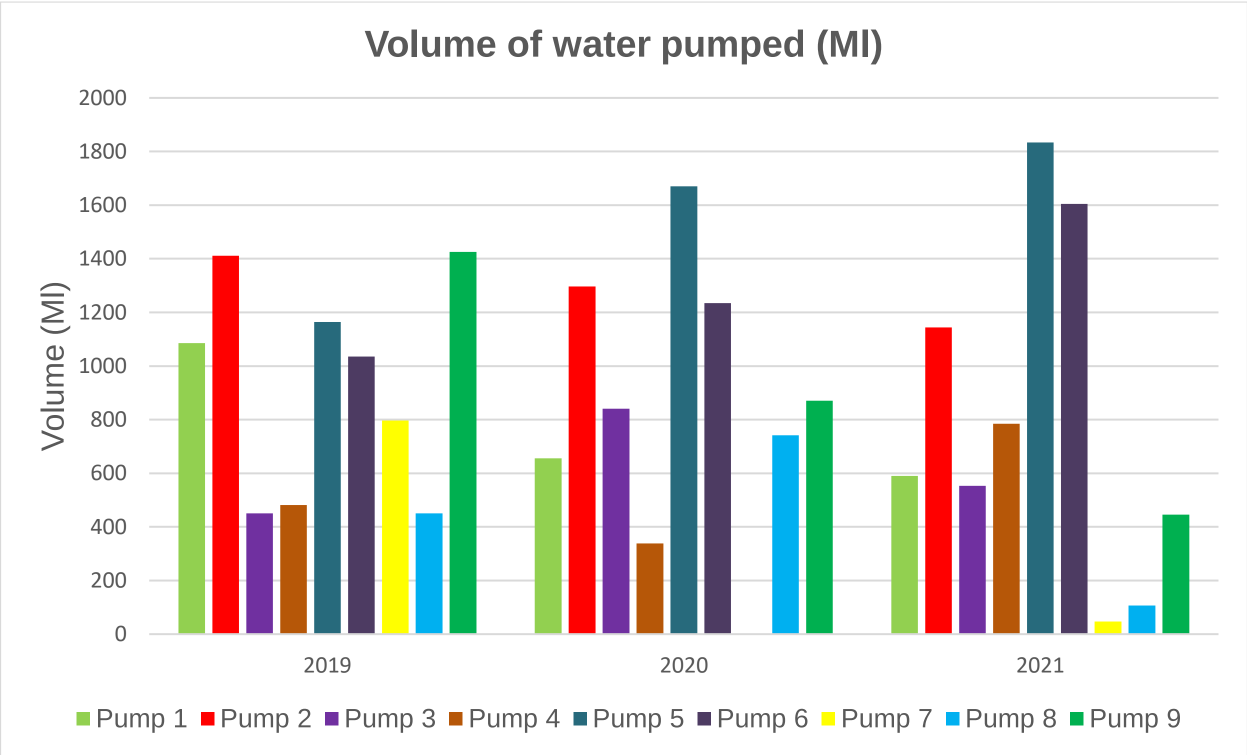

Figure 4-48: Volume of water pumped by each pump (Ml)

4.2.6 Analysis 6: Gross financial losses

From the results of analyses 3, 4 and 5, the financial losses can be calculated for the pump station. The volume of water pumped per pump as calculated in analysis 5 was multiplied by the effective cost (R/Ml) of each pump to determine the baseline cost of each pump for 2019, 2020 and 2021. The baseline operational cost for each pump is shown in Table 4-6 and graphically presented in Figure 4-49. From the pump curve in Figure 4-35, it can be seen that the pump efficiency can not exceed 80% at the pump station's specific operational conditions. From analysis 3 it can be seen that pump 9 has the highest pump efficiency of 79.4%. To calculate the financial losses, pump 9 was used as the theoretical maximum efficiency. The other pumps in the pump station were theoretically refurbished by making the other pumps as efficient as pump 9. The effective cost (R/Ml) of pump 9 was multiplied by the volume of water pumped by each pump, to determine the theoretical operational cost. The theoretical operational cost of each pump is shown in Table 4-7 and graphically presented in Figure 4-50. The gross financial losses were calculated by subtracting the theoretical operational cost from the baseline cost. The gross financial losses for each pump during 2019, 2020 and 2021 are shown in Table 4-8 and graphically represented in Figure 4-51.

Table 4-6: Baseline operational cost

		Baseline operational cost (R)		
Pump column	**Pump number**	**2019**	**2020**	**2021**
Column 1	Pump 1	R2 706 403,67	R1 764 147,82	R1 820 685,42
	Pump 2	R3 447 842,18	R3 638 365,13	R4 048 835,00
	Pump 3	R1 165 587,85	R2 475 635,27	R2 063 903,57
Column 2	Pump 4	R1 279 774,93	R880 719,43	R2 708 858,98
	Pump 5	R2 887 226,41	R4 585 667,61	R6 325 744,91
	Pump 6	R2 661 040,26	R3 398 984,05	R5 587 435,69
Column 3	Pump 7	R2 092 185,71	R-	R148 346,83
	Pump 8	R1 334 096,78	R2 212 823,89	R416 543,53
	Pump 9	R3 408 117,34	R2 215 674,07	R1 364 052,93

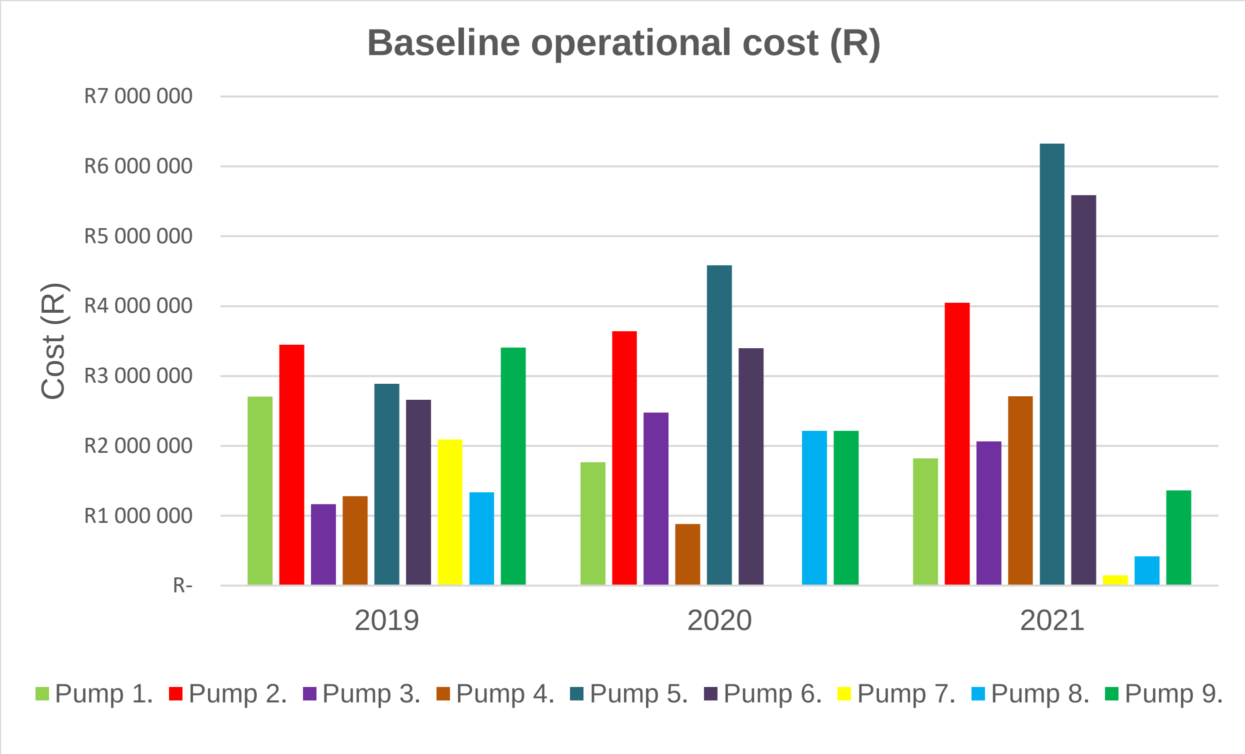

Figure 4-49: Baseline operational cost

Table 4-7: Theoretical operational cost

		Theoretical operational cost (R)		
Pump column	**Pump number**	**2019**	**2020**	**2021**
Column 1	Pump 1	R2 607 922,70	R1 699 953,78	R1 754 434,08
	Pump 2	R3 325 485,01	R3 509 246,68	R3 905 149,78
	Pump 3	R1 097 396,58	R2 330 801,28	R1 943 157,44
Column 2	Pump 4	R1 148 685,27	R790 505,74	R2 431 385,66
	Pump 5	R2 803 702,37	R4 453 009,68	R6 142 748,60
	Pump 6	R2 543 640,96	R3 249 028,29	R5 340 930,21
Column 3	Pump 7	R1 921 050,85	R-	R136 212,48
	Pump 8	R1 140 828,81	R1 892 256,46	R356 199,69
	Pump 9	R3 408 117,34	R2 215 674,07	R1 364 052,93

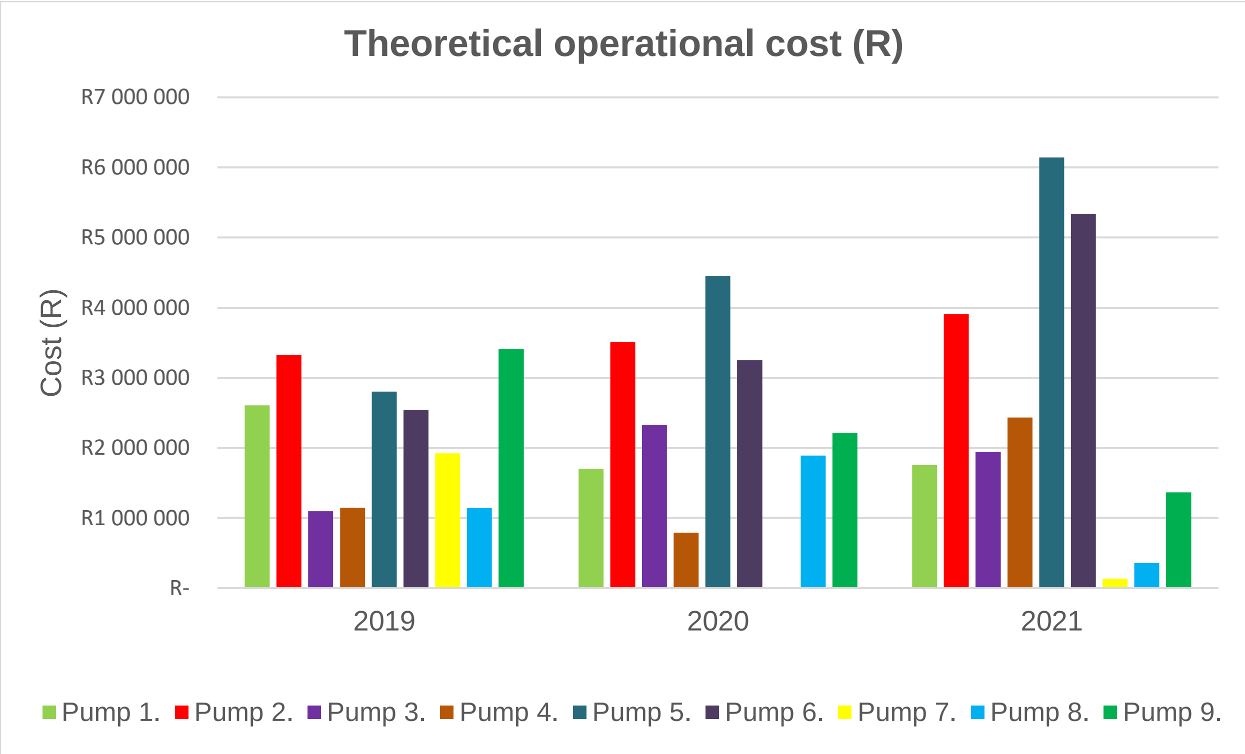

Figure 4-50: Theoretical operational cost

Table 4-8: Gross financial losses

		Gross financial losses (R)			
Pump column	**Pump number**	**2019**	**2020**	**2021**	**Total**
Column 1	Pump 1	R98 480,97	R64 194,04	R66 251,34	R228 926,34
	Pump 2	R122 357,16	R129 118,45	R143 685,22	R395 160,84
	Pump 3	R68 191,28	R144 833,98	R120 746,13	R333 771,39
Column 2	Pump 4	R131 089,66	R90 213,68	R277 473,32	R498 776,66
	Pump 5	R83 524,04	R132 657,93	R182 996,30	R399 178,27
	Pump 6	R117 399,29	R149 955,77	R246 505,48	R513 860,54
Column 3	Pump 7	R171 134,86	R-	R12 134,35	R183 269,21
	Pump 8	R193 267,97	R320 567,44	R60 343,84	R574 179,25
	Pump 9	R-	R-	R-	R-
Total		**R985 445,23**	**R1 031 541,28**	**R1 110 135,98**	**R3 127 122,50**

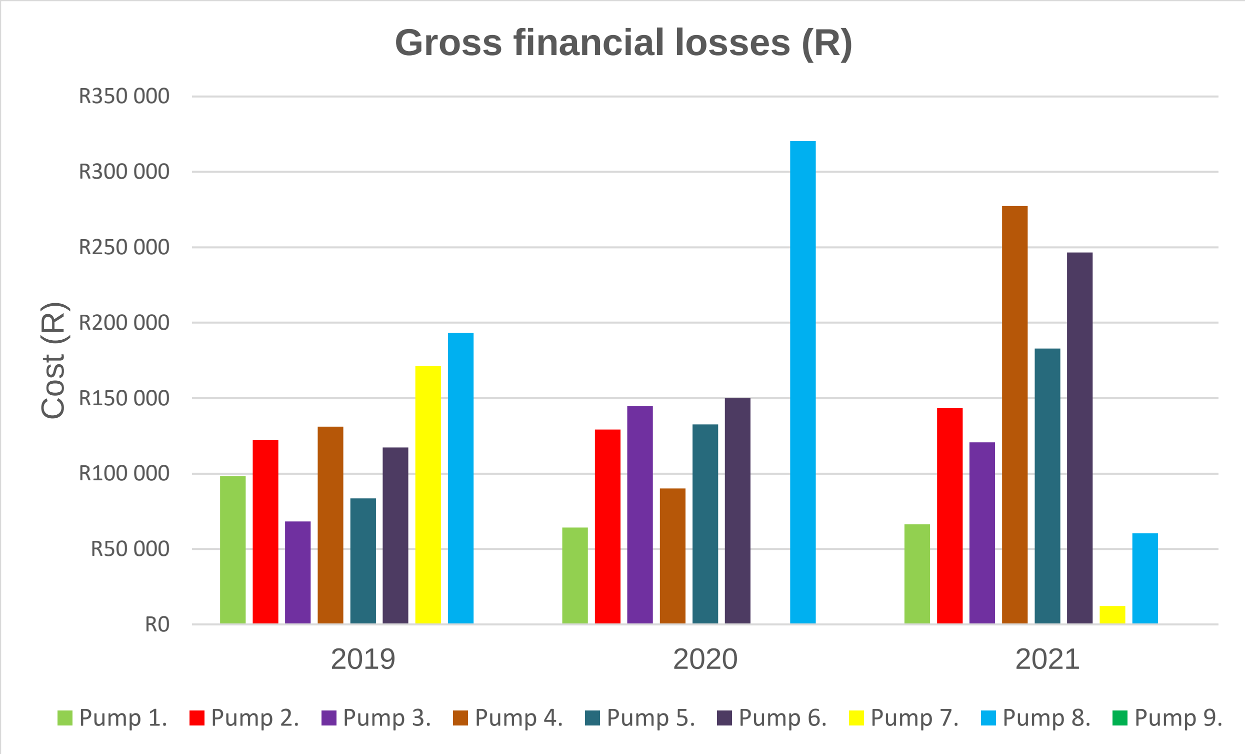

Figure 4-51: Gross financial losses

4.2.7 Nett financial losses

The Nett financial losses are determined by comparing the operational financial losses with the capital investment required to refurbish a pump. There was not sufficient information obtainable from the mine regarding the capital investment required to refurbish the specific pumps analysed in the study. The only value that was obtainable was a similar pump that was refurbished in 2020 at a cost of R1 132 000,00. From Table 4-9 it is clear that an accurate nett financial loss can not be calculated, since the data for the analysis was only available for three consecutive years. Table 4-9 shows that some pumps have been in operation for more than 10 years. The utilisation of these pumps plays a significant role in the efficiency degradation and financial losses of the pump. Without knowing the efficiency change over time and the utilisation for the total lifetime of the pump, the Nett financial losses can not be calculated.

Table 4-9: Pump summary from 2019 to 2021

		2019 - 2021		
Pump number	**Years in operation**	**Efficiency (%)**	**Average Utilisation (%)**	**Total financial losses (R)**
Pump 1	11	76,5%	9,9%	R228 926,34
Pump 2	7	76,6%	16,2%	R395 160,84
Pump 3	9	74,8%	8,6%	R333 771,39
Pump 4	8	71,3%	6,5%	R498 776,66
Pump 5	7	77,1%	19,4%	R399 178,27
Pump 6	10	75,9%	17,8%	R513 860,54
Pump 7	12	72,9%	3,9%	R183 269,21
Pump 8	14	67,9%	7,0%	R574 179,25
Pump 9	4	79,4%	10,7%	R-

4.3 Discussion of results

4.3.1 Technical related

It is common for companies to monitor various parameters of pumping operations, to determine operational performance. These parameters are primarily monitored to ensure the equipment meets operational requirements. Some companies use measured parameters like volume flow rate, pressure and electricity consumption of pumps to predict equipment failure. The prediction of equipment failure can be used to develop predictive maintenance strategies that allow the replacement or refurbishment of equipment before complete failures result in financial losses as a result of unplanned downtime. The measured parameters can also be used to determine the operational cost of pumps. It is important to measure the operational cost of pumps since the operational cost far exceeds the initial investment of the pump. The depreciation of pump efficiency will increase the operational cost of a pump because the conversion of electrical power to hydraulic power becomes less efficient. The pump produces a lower flow at constant pressure while consuming the same amount of electrical energy, therefore a low-efficiency pump needs to operate longer to achieve the same result as a high-efficiency pump.

Large multi-stage centrifugal pumps are used in the deep-level mining industry to dewater the mine. Very little attention is given to these pumps' efficiency degradation, as these pumps are extremely reliable and can achieve their operational requirements for more than 10 years if the water quality is good. The efficiency degradation rate of pumps is unpredictable, due to factors like water quality and pump material quality affecting the rate of degradation.

The dynamic nature of the operational requirements of pumping systems and the availability of equipment makes it difficult to predict possible financial losses. The utilisation of individual pumps in a pumping system has a direct impact on operational costs. From the literature, it is clear that the most accurate method to determine financial losses is with data-driven analysis methods. A data-driven analysis method was used to calculate the baseline energy cost and efficiency for a specific pumping station on a deep-level gold mine in South Africa. The baseline model was further analysed in detail, to determine the baseline operational cost and efficiency of individual pumping columns and pumps within the pumping station. The detailed analysis of the individual pumps revealed what effect utilisation and efficiency of individual pumps have on the overall operational cost of the pumping system.

The baseline analysis done on the whole pumping system is summarised in Table 4-10. The operational efficiency of the pumping system was determined in terms of kWh/Ml and percentage pump efficiency. The kWh/Ml was used to calculate the effective cost (R/Ml) by multiplying the electricity tariff (R/kWh) with the operational efficiency (kWh/Ml) of pumping a fixed volume of water, while the percentage pumping system efficiency was used to understand how much the pump station can be improved.

Table 4-10: Summary of the pump station's baseline analysis

Year	Average electricity tariff (R/kWh)	System Efficiency (%)	System Efficiency (kWh/Ml)	Effective cost (R/Ml)
2019	0.85	74,8%	3103,14	R 2637,67
2020	0.93	73,8%	3155,88	R 2934,97
2021	1.10	73,5%	3165,84	R 3482,43

The baseline analysis done on the individual pumps is summarised in Table 4-11. The pump efficiency, utilisation and effective operational cost of each pump were calculated, to determine the degradation of each pump, as well as the effective operational cost relating to each pump's efficiency. The baseline parameters calculated for each pump were used to understand the effect of pump utilisation on the overall operational cost, as well as to determine each pump's severity of efficiency degradation.

Table 4-11: Summary of the individual pumps' baseline analysis

		Average from 2019 to 2021		
Pump column	**Pump number**	**Efficiency (%)**	**Utilisation (%)**	**Effective cost (R/Ml)**
Column 1	Pump 1	76,5%	9,9%	R 2 930,01
	Pump 2	76,6%	16,2%	R 2 927,27
	Pump 3	74,8%	8,6%	R 2 998,83
Column 2	Pump 4	71,3%	6,5%	R 3 145,60
	Pump 5	77,1%	19,4%	R 2 907,50
	Pump 6	75,9%	17,8%	R 2 953,70
Column 3	Pump 7	72,9%	3,9%	R 3 074,91
	Pump 8	67,9%	7,0%	R 3 301,70
	Pump 9	79,4%	10,7%	R 2 823,39

The individual pump efficiency was used to identify the highest-efficiency pump in the pump station. The pump with the highest efficiency was compared with the pump curve, to determine if the pump has a higher theoretical efficiency at the operating condition. The pump with the highest efficiency (Pump 9) ran close to the theoretical efficiency point of 80%, therefore the actual effective cost of the pump was used as the parameters for a refurbished pump.

The volume of water pumped by each pump was determined to calculate the actual operational cost of each pump. The volume of water pumped (Ml) was multiplied by the effective rate (R/Ml) of each pump to determine the baseline operational cost of the pump station. The baseline operational cost of the pump station is summarised in Table 4-12. After the baseline cost was calculated, the volume of water pumped per pump was multiplied by the effective rate (R/Ml) of the most efficient pump (Pump 9). This was done to theoretically "refurbish" the low-efficiency pumps and calculate the predicted operational cost of the pump station. The predicted operational cost of the pump station is summarised in Table 4-12. The gross financial losses were calculated by subtracting the predicted operational cost from the baseline operational cost as summarised in Table 4-12.

Table 4-12: Summary of the gross financial losses

Pump number	Baseline operational cost (R)	Predicted operational cost (R)	Gross financial losses (R)
Pump 1	R6 291 236,90	R6 062 310,56	R228 926,34
Pump 2	R11 135 042,31	R10 739 881,47	R395 160,84
Pump 3	R5 705 126,69	R5 371 355,30	R333 771,39
Pump 4	R4 869 353,34	R4 370 576,67	R498 776,66
Pump 5	R13 798 638,93	R13 399 460,65	R399 178,27
Pump 6	R11 647 460,00	R11 133 599,46	R513 860,54
Pump 7	R2 240 532,53	R2 057 263,32	R183 269,21
Pump 8	R3 963 464,20	R3 389 284,96	R574 179,25
Pump 9	R6 987 844,34	R6 987 844,34	R-
Total	**R66 638 699,24**	**R63 511 576,74**	**R3 127 122,50**

4.3.2 Business related

The results summarised in section 4.3.1 revealed that financial losses of more than R 3 million occurred in a single pump station on a deep-level gold mine in South Africa due to pump efficiency degradation. The gross financial losses occurred over three years as a result of increased electrical energy consumption caused by the operation of inefficient pumps. The efficiency degradation of individual pumps was not noticeable in the measured three years, but the effective operational cost increased as a result of pump utilisation and the increase of electricity tariffs. The actual Nett financial losses could not be accurately calculated because of two reasons. The first is that only a single value was obtainable that specifies the refurbishment cost of a similar pump. The second reason is that not sufficient data was available before 2019, therefore the operational cost over each pump's lifetime could not be calculated.

Even though the Nett financial losses could not be calculated, it is clear that it is beneficial for companies to do condition monitoring on pumps, not only just for failure prediction, but also for monitoring financial losses. The least efficient pump in the pump station accumulated 50% of the refurbishment cost in only three years. The pump has been in operation for 18 years and was only utilised 7% in the three years. Therefore it can be estimated with a high level of confidence that the pump's energy losses have far exceeded the refurbishment cost of the pump.

The pumping station analysed in this study contributes only 7.5% to the mine's total pumping electricity cost. The pumping station only pumps clean fissure water unlike the other pumping stations that pump fissure water and dirty mine water. The specific pumping station implements an effective load-shifting scheme that reduces the energy tariff. From the literature, it was noted that poor water quality can increase pump efficiency degradation. In addition to poor water quality, the continuous increase of electricity tariffs increases the operational cost of pumps even if the efficiency does not decrease significantly. As noted in the analysis phase, the utilisation of pumps also affect the operational cost of pumping stations. By considering all these aspects, it is crucial for the mine to continuously monitor the condition of its pumps and do predictive maintenance to reduce financial losses caused by inefficient pumping systems. The predictive maintenance must primarily be based on energy losses and not necessarily on failure prediction. The predictive maintenance strategy can be based on the model proposed by Beebe and Beebe (2004:61). Beebe and Beebe (2004:61) stated that if the pump degradation increases with time, the optimum refurbishment point will be when the accumulated cost of the energy losses equals the cost of refurbishment. If the refurbishment cost exceeds the accumulated financial cost, the investment made to refurbish the pump will not be regained through energy savings as shown in Figure 4-52. If the accumulated energy losses exceed the financial investment of pump refurbishment, a financial loss occurs that can not be regained, as shown in Figure 4-53. If the accumulated energy losses are equal to the refurbishment cost, the financial inventment made to refurbish the pump will be repaid by the electricity cost saved, as shown in Figure 4-54. Figure 4-52, Figure 4-53 and Figure 4-54 serve only as an illustration, thus it does not contain actual data like tariff increases, actual refurbishment cost and pump degradation rates.

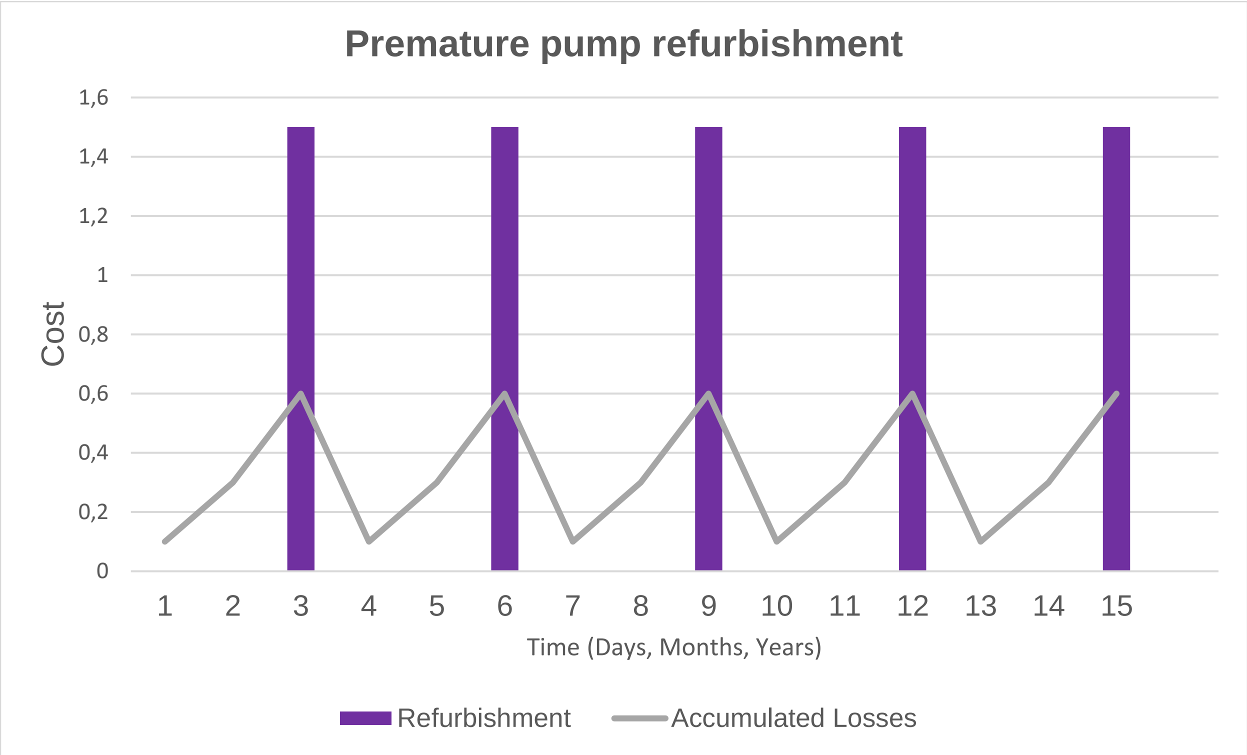

Figure 4-52: Premature pump refurbishment

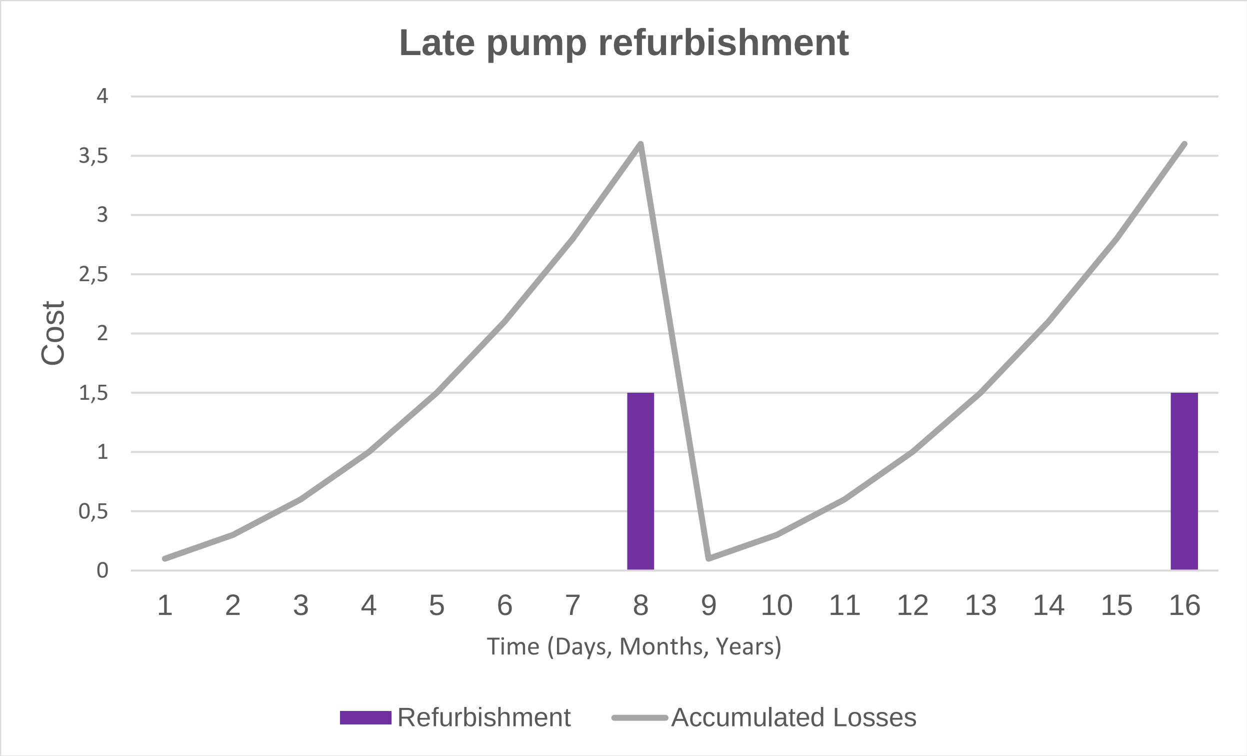

Figure 4-53: Late pump refurbishment

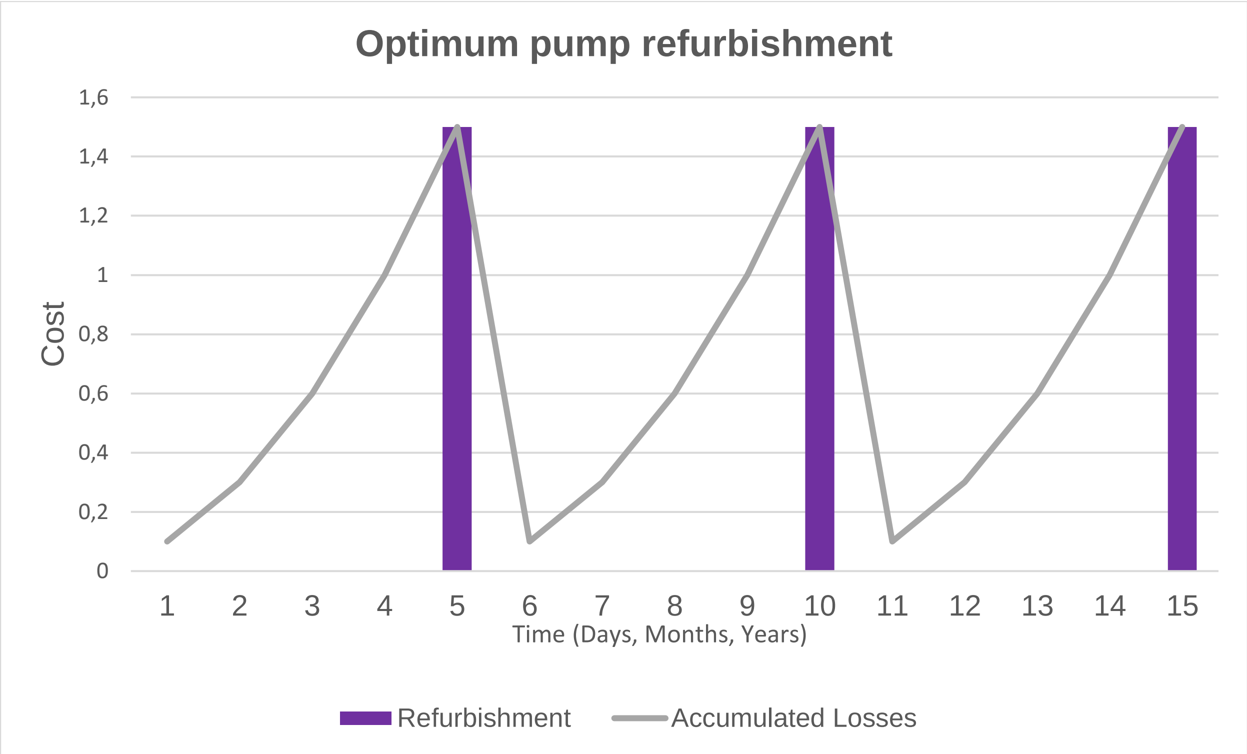

Figure 4-54: Optimum pump refurbishment

From the analysis, it is clear that pump utilisation has an impact on the operational cost of a pump station. The methodology used to calculate the baseline operational cost of a pumping system can be used to improve pump scheduling. The increased utilisation of inefficient pumps increases the operational cost of a pumping system. By improving the scheduling of pump utilisation, the mine can reduce operational costs without investing significant capital.

The results of this study prove the importance of monitoring pumps for energy losses, as it can have a significant impact on operational costs. Simple equipment used to measure pump performance for operational parameters and predictive maintenance strategies can be used to determine pump efficiency. The timely refurbishment of pumps can significantly reduce operational costs, which increases profit margins and improve the company's competitive advantage.

4.4 Summary

The literature revealed that pump efficiency degradation is unpredictable due to the many factors that can impact the degradation rate. The energy losses caused by pump efficiency degradation were determined with data-driven analysis. The literature also suggests that pump performance analysis can be done with installed measuring equipment. The measured performance data captured on the mine's historical server was used to do performance analysis on a pump station in the mine.

The actual operational cost at exiting efficiency was calculated to determine the baseline operational cost. The individual efficiencies of the pumps within the pump station were calculated to identify the efficiency increase required, to develop a prediction model. One pump within the pump station ran at the best efficiency point (BEP), which meant that the parameters of that specific pump could be used to develop the prediction model. The pump parameters of this pump were used to substitute the performance of the other pumps in the baseline model. The predicted operational cost was calculated, by predicting that the other pumps would have run at the same parameters if they were refurbished.

The difference between the baseline operational cost and the predicted operational cost resulted in the financial losses that occurred over the analysed period. The gross financial losses suffered by the pump station are more than R3 million. Only a third of the pumps contributed to more than half of the financial losses. Even though the Nett financial losses could not be calculated, it is clear that it is beneficial for companies to do condition monitoring on pumps, not only just for failure prediction, but also for monitoring financial losses. The least efficient pump in the pump station accumulated 50% of the refurbishment cost in only three years. The pump has been in operation for 14 years and was only utilised 7% in the three years. Therefore it can be estimated with a high level of confidence that the pump's energy losses have far exceeded the refurbishment cost of the pump. It is recommended that deep-level mines implement performance measurement strategies on pumping stations, as significant financial losses can go unnoticed.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The backbone of the South African economy is the mining industry, who employs more people directly and indirectly than any other economic sector. The largest contributor to the country's Gross domestic product (GDP) is the mining industry, which contributes approximately 7.5% to the GDP (Khubana, 2021:1). A global downward trend in terms of productivity and a return on invested capital is experienced in the mining industry of approximately 4% per annum, with a reported 30-year low in 2015 (McKinsey, 2017:4).

High operating costs are a major concern for South African mines, which can lead to a reduction in mine life (Maregedze *et al.*, 2022:2). The electricity cost makes up approximately 20% of the operating cost of a deep-level mine. . The high operational cost associated with electricity prices in South Africa is the primary reason why mining operations are declining (Neingo & Tholana, 2016:283). The South African mining industry is a large consumer of electricity; consuming more than 10% of the country's generated electricity (Ratshomo & Nembahe, 2019:36). The gold mines are the highest consumer of electricity across the mining sector; consuming almost as much as all the other mining sectors combined (Mare *et al.*, 2016:112-117).

Eight of the world's ten deepest mines are gold mines situated in the Witwatersrand basin in South Africa (Nex & Kinnaird, 2019:32). One of the biggest challenges of these extreme depths is the high underground temperatures (Groenewald *et al.*, 2013:2). Significant mine cooling systems (MCSs) are required to operate a mine at such extreme depths. The MCSs are used to ensure the underground working conditions in the mine are below the legal limit of 32ºC wet bulb, consisting of water reticulation (pumping) and refrigeration sub-systems. The MCSs consume approximately 41% of the total electricity supplied to deep-level mines (Maré, 2017:4).

Due to the high volumes of water collected underground, the mine must be dewatered to continue mining operations. The dewatering process is a necessity for the continuous operation of the mine, and therefore needs to be controlled efficiently. The dewatering system uses multiple high-performance pumps to dewater the mine (Groenewald *et al.*, 2013:1-4). The world's largest hydraulic heads are found in South African gold mines.

The high hydraulic heads and high volumes to be dewatered place additional strain on deep-level mines, due to the high electricity consumption associated with pumping systems (Winde *et al.*, 2017:679). Multi-stage centrifugal pumps are mainly used in deep-level mines due to the high static head created by the extreme depths (Schoeman, 2014:31).

Due to the reliability of multi-stage centrifugal pumps, little information is known about performance changes during the pump's operation (Eaton *et al.*, 2018:1). Over the lifetime of the pump, the inefficiencies will decrease and result in increased long-term costs. The performance decrease is usually realised once a significant reduction in performance affects the whole system driven by the pump. The most prominent attribute to the decrease in pump performance; is a pump's degradation over time, yet; no adequate relationship has been developed between the two (Eaton *et al.*, 2018:1).

Pump efficiency degradation is caused by pump wear. The amount of internal wear that a pump can tolerate depends on the kind of pump and the system characteristics it operates in. Pumps with high specific speeds exhibit a much smaller relative power increase as a result of internal wear, but the energy increase may still be substantial due to the size of these pumps (Beebe & Beebe, 2004:28). A decreasing efficiency is indicated by increased power consumption. Lower efficiency means that the pump will need to run for longer to move the same amount of fluid. Performance monitoring and condition monitoring of a pump can indicate when a pump should be refurbished (Oberholzer, 2015:16).

Improving the effectiveness of water and energy use is a key objective for the mining industry in a time of high energy costs and growing sustainability concerns (Vosloo *et al.*, 2012:328). Various authors have proposed energy efficiency strategies for pumping systems, including maintenance and online monitoring, assessment and reporting, and design and calibration (Torregrossa *et al.*, 2017:1431). . The prediction technique is an adapted bottom-up energy efficiency and saving calculation (Grillone *et al.*, 2020:3). An adapted bottom-up energy efficiency and saving calculation to predict possible energy savings is possible by determining energy losses (Reichl & Kollmann, 2011:423).

The need was identified to investigate the financial impact of energy losses due to pump efficiency degradation in South African deep-level mines. An in-depth literature review was conducted on the measurement and quantification of pump efficiency degradation. Literature relating to the energy consumption increase as a result of reduced pump efficiency was also evaluated. The literature revealed that pump performance measurement will reveal the condition of a pump, and the associated energy consumed in relation to the efficiency of the pump. The most common method used to determine energy losses that occurred as a result of efficiency reduction is a data-driven saving prediction method.

The financial impact of energy losses caused by pump efficiency degradation was determined by comparing the baseline energy cost of a pumping station, with the predicted energy cost had the pump efficiency been restored to the original condition. The difference between the two cost models resulted in the financial losses incurred.

5.2 Results

The primary baseline models were created using a data-driven method. The baseline data used for this study spanned from 2019 to 2021. Data from 2018 was excluded because all the relevant data was not available. The first baseline model determined the performance of each pump within the pump station and the effective cost of each pump. The baseline performance of each pump is summarised in Table 5-1.

Table 5-1: Baseline performance of each pump

		Average from 2019 to 2021		
Pump column	**Pump number**	**Efficiency (%)**	**Utilisation (%)**	**Effective cost (R/Ml)**
Column 1	Pump 1	76,5%	9,9%	R 2 930,01
	Pump 2	76,6%	16,2%	R 2 927,27
	Pump 3	74,8%	8,6%	R 2 998,83
Column 2	Pump 4	71,3%	6,5%	R 3 145,60
	Pump 5	77,1%	19,4%	R 2 907,50
	Pump 6	75,9%	17,8%	R 2 953,70
Column 3	Pump 7	72,9%	3,9%	R 3 074,91
	Pump 8	67,9%	7,0%	R 3 301,70
	Pump 9	79,4%	10,7%	R 2 823,39

The volume of water pumped by each pump was determined to calculate the actual operational cost of each pump. The volume of water pumped (Ml) was multiplied by the effective rate (R/Ml) of each pump to determine the baseline operational cost of the pump station. The baseline operational cost of the pump station is summarised in Table 5-2.

After the baseline cost was calculated, the volume of water pumped per pump was multiplied by the effective rate (R/Ml) of the most efficient pump (Pump 9). This was done to theoretically "refurbish" the low-efficiency pumps and calculate the predicted operational cost of the pump station. The predicted operational cost of the pump station is summarised in Table 5-2. The gross financial losses were calculated by subtracting the predicted operational cost from the baseline operational cost as summarised in Table 5-2.

Table 5-2: Summary of the baseline cost, predicted cost and gross financial losses

Pump number	Baseline operational cost (R)	Predicted operational cost (R)	Gross financial losses (R)
Pump 1	R6 291 236,90	R6 062 310,56	R228 926,34
Pump 2	R11 135 042,31	R10 739 881,47	R395 160,84
Pump 3	R5 705 126,69	R5 371 355,30	R333 771,39
Pump 4	R4 869 353,34	R4 370 576,67	R498 776,66
Pump 5	R13 798 638,93	R13 399 460,65	R399 178,27
Pump 6	R11 647 460,00	R11 133 599,46	R513 860,54
Pump 7	R2 240 532,53	R2 057 263,32	R183 269,21
Pump 8	R3 963 464,20	R3 389 284,96	R574 179,25
Pump 9	R6 987 844,34	R6 987 844,34	R-
Total	**R66 638 699,24**	**R63 511 576,74**	**R3 127 122,50**

The results summarised in Table 5-2 revealed that financial losses of more than R 3 million occurred in a single pump station on a deep-level gold mine in South Africa due to pump efficiency degradation. The gross financial losses occurred over three years as a result of increased electrical energy consumption caused by the operation of inefficient pumps. The efficiency degradation of individual pumps was not noticeable in the measured three years, but the effective operational cost increased as a result of pump utilisation and the increase of electricity tariffs. The actual Nett financial losses could not be accurately calculated because of two reasons. The first is that only a single value was obtainable that specifies the refurbishment cost of a similar pump. The second reason is that not sufficient data was available before 2019, therefore the operational cost over each pump’s lifetime could not be calculated.

5.3 Conclusion

Pump scheduling and maintenance management is not done efficiently in the gold mining industry, due to the high quantity of variables involved. Due to the high reliability of these machines; little to no attention is given to the losses occurring due to efficiency losses (Beebe & Beebe, 2004:3). A typical deep mine has a high quantity of high-demand pumps, to dewater the mine. A small efficiency change in these pumps will have a significant financial impact (Beebe, 2012:34-40). Determining the efficiency of a pump is widely known, but is rarely linked to a monetary value. The monetary impact is ever-increasing, due to the constant cost increase in electrical charges (Labuschagne, 2020:2).

The degradation of pumps is a crucial component in forecasting financial losses caused by efficiency losses. The degradation of a pump cannot be predicted, and therefore needs to be monitored constantly to make an accurate prediction.

Maintenance on pumps is usually done, based on the original equipment manufacturer’s (OEM) recommendations, and not according to actual performance. The refurbishment of pumps is not considered necessary by operational departments if operational requirements are achieved, and the capital expenditure required to refurbish a pump is not deemed necessary by the financial department if the pump performs its duty according to the operational departments

Even though the Nett financial losses could not be calculated, it is clear that it is beneficial for companies to do condition monitoring on pumps, not only just for failure prediction, but also for monitoring financial losses. The least efficient pump in the pump station accumulated 50% of the refurbishment cost in only three years. The pump has been in operation for 14 years and was only utilised 7% in the three years. Therefore it can be estimated with a high level of confidence that the pump’s energy losses have far exceeded the refurbishment cost of the pump. It is recommended that deep-level mines implement performance measurement strategies on pumping stations, as significant financial losses can go unnoticed. The results from performance measurement can be used to improve maintenance strategies and pump scheduling. The financial losses relating to pump efficiency degradation will only become more significant with time, as efficiency decrease over time, and energy tariffs increase.

5.4 Achievement of the study objectives

The primary objective of the study is to determine the financial impact of energy losses due to pump efficiency degradation in South African deep mines. The existing research was reviewed to provide context on the operational requirements of pumping systems in deep-level mines. The type of pumps, as well as the scheduling of pumps, were analysed to determine the impact of pump operating conditions on the system efficiency. The technical aspects relating to pump efficiency calculations were researched and analysed, to calculate the efficiency degradation of the pumps. The existing research was reviewed and analysed, to determine the correlation between efficiency degradation and energy losses. The technical aspects relating to pump efficiency and operational cost, as well as the correlation between pump efficiency degradation and energy losses are presented in Chapter 2.

A detailed literature review was conducted to evaluate the methods commonly used to determine financial losses as a result of inefficient equipment. This literature review was not limited to the deep-level mining industry. The primary research objective of this study was solved with the research findings obtained by the literature review.

The relevant parameters of pump efficiency, energy consumption, and energy cost measured on the mine were analysed and presented in Chapter 4. The baseline performance for the whole pump station in terms of the volume of water pumped, energy consumption and energy tariffs were determined through the development of a historical data-driven model. The individual aspects of the baseline model were further broken down to determine the operational performance of the individual columns and pumps within the pump station. The baseline operational cost of the system was calculated, to provide a baseline operational cost.

The difference between the baseline model and the improved baseline model was compared to calculate the energy losses that occurred as a result of the efficiency degradation of the pumps. The predicted energy reduction was based on the information analysed in the existing literature. By translating the electrical energy losses into financial losses and taking into account the appropriate electricity cost tariffs, the financial value of operational losses was calculated.

To determine how a pump's efficiency degradation is measured, the existing literature was reviewed, to determine the methods used to calculate pump efficiency. The technical aspects relating to pump efficiency calculations were researched and analysed, to calculate the efficiency degradation of the pumps. The technical aspects relating to pump efficiency calculations are presented in Chapter 2.

To determine the correlation between pump efficiency degradation and electrical energy consumption, the existing literature reviewed in Chapter 2 was applied to develop mathematical models that indicated the relationship between the two variables.

To calculate the financial losses incurred as a result of pump efficiency degradation, an energy-saving prediction model was developed as prescribed by the literature in Chapter 2. A time series forecasting model was used to develop baseline models and prediction models were used to calculate the gross financial losses incurred. The analyses are presented in Chapter 4.

Even though the Nett financial losses could not be calculated, it is clear that it is beneficial for companies to do condition monitoring on pumps, not only just for failure prediction, but also for monitoring financial losses. The least efficient pump in the pump station accumulated 50% of the refurbishment cost in only three years. The pump has been in operation for 18 years and was only utilised 7% in the three years. Therefore it can be estimated with a high level of confidence that the pump's energy losses have far exceeded the refurbishment cost of the pump.

5.5 Limitations of the study

The study aimed to quantify the energy losses of the pumping station as accurately as possible, to determine if the energy losses exceed the capital investment required to improve the pump efficiency through refurbishment. The literature suggests that the rate of pump degradation can not be accurately predicted, only measured. Since there were only three years of historical data available, the total operational losses can only be extrapolated and not verified with a high level of certainty. An additional limitation is the actual cost of pump refurbishment, as some information was gathered from the mine, but the cost may vary depending on the degree of internal pump damage.

5.6 Recommendations for further research

This study did not evaluate all the aspects that can contribute to financial losses in pumping systems. Yates and Weybourne (2001:111) stated: “Pump and pipework losses have the most significant impact on the overall efficiency of a well-designed pumping system.” Studies on the contribution to energy losses caused by other components like pipework can add significant value to the field energy efficiency improvement in deep-level mine pumping stations.

No literature is available regarding the relationship between pump degradation severity and the financial cost of pump refurbishment. If refurbishment cost changes in relation to the severity of pump efficiency degradation, the information can be used to develop a pump refurbishment model.

A qualitative research study can be developed to quantify the knowledge barriers relating to efficiency improvement between financial, operational and maintenance departments in various industries. The significant financial losses indicate that the technical aspects of efficiency improvement hinder non-technical departments from realising the financial benefit of investing in efficiency improvement projects.

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