# Quantifying the cost of pump efficiency decay on the Department of Water and Sanitation

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# ABSTRACT

**Title:** Quantifying the cost of pump efficiency decay on the Department of Water and Sanitation

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**Keywords:** Efficiency decay, Bulk water distribution, Centrifugal pumps, Operating costs

By analysing the usage of water in South Africa, together with the energy consumption from pumps in the industry, it is easy to identify a problem. A need exists in determining what influence the decay in efficiency of bulk water pumps has on energy costs. Of all the water supplied to consumer units during 2013, 44.7% of this water was supplied free of charge, making the need to supply water as efficiently as possible a great concern. The average energy component of the life cycle cost of a pump accounts for about 60% of the cost.

The literature study in this dissertation focuses on the operation, maintenance and monitoring of centrifugal pump systems. A detailed investigation on symptoms that cause efficiency decay of a centrifugal pump system was done. This investigation was used to determine the average efficiency loss and possible efficiency gain that could be realised given that the correct monitoring and maintenance procedures are implemented on the pump system. This study was used to simulate the operation of well monitored and maintained centrifugal pumps.

The operational simulation of the centrifugal pumps was done where maintenance was simulated by reinstating the pumps' original efficiency after a certain maintenance period. The maintenance period was determined by making use of a Pump Energy Indicator. The cumulative additional operational costs (energy costs) were calculated using a simulated maintained pump and a simulated unmaintained pump. The potential savings for maintaining a high pump system efficiency was determined.

The simulation was done on a total of fourteen centrifugal pump systems. The results showed that, if possible, the correct operation, maintenance and monitoring of centrifugal pump systems could spare a substantial amount of energy costs. From the fourteen cases, the average energy cost savings calculated to 0.29 R/kW/h.

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## NOMENCLATURE

| **Symbol** | | **Description** |
|---|---|---|
| $\Delta P$ | - | Differential pressure over the pump |
| $\Delta t$ | - | Differential time |
| A | - | Active energy charge |
| a | - | The y-intercept of the graph |
| An | - | Ancillary service charge |
| As | - | Affordability subsidy charge |
| b | - | Efficiency decay |
| b | - | The slope of the graph |
| C | - | Network capacity charge |
| D | - | Diameter |
| D | - | Network demand charge |
| $E_i$ | - | Total energy entering the system boundary |
| $E_o$ | - | Total energy leaving the system boundary |
| $E_t$ | - | Total energy leaving the system boundary |
| g | - | Gravitational acceleration 9.81 $m/s^2$ |
| h | - | Hours |
| H | - | Total head developed in metres |
| $h_f$ | - | Total head loss due to friction losses between the points |
| $h_l$ | - | Total head loss due to friction and minor losses between the points |
| $h_m$ | - | Total head loss due to minor losses between the points |
| i, o | - | In, out respectively |
| j | - | At time step j |
| K | - | Minor loss coefficient |
| k | - | Number of pump sets in parallel |
| l | - | Total amount of |
| m | - | Number of energy entering points |
| N | - | Impellor rotational speed |
| n | - | Number of energy leaving points |
| n | - | The total number of data points |
| $N_s$ | - | Pump specific speed index number |
| P | - | Pressure |

$P_h$ - Hydraulic power
$P_t$ - Total power
$Q$ - Flow rate
$r$ - Correlation coefficient
$Re$ - Reactive energy charge
$R_j$ - Cost at time step j
$S$ - Electrification & rural network subsidy charge
$t$ - Time
$t$ - Total amount of
$T$ - Transmission network charge
$V$ - Flow velocity
$Z$ - Elevation
$\eta_m$ - Motor efficiency
$\eta_p$ - Pump efficiency
$\eta_s$ - Pump set efficiency
$\rho$ - Fluid density

# ABBREVIATIONS

| **Abbreviation** | | **Description** |
|---|---|---|
| AOR | - | Allowable Operating Region |
| BEP | - | Best Efficiency Point |
| CAC | - | Cumulative Additional Cost |
| CBM | - | Condition Based Maintenance |
| CPU | - | Central Processing Unit |
| DCS | - | Distributed Control Systems |
| DSM | - | Demand Side Management |
| DWA | - | Department of Water Affairs |
| DWAF | - | Department of Water Affairs and Forestry (currently DWS) |
| DWS | - | Department of Water and Sanitation |
| EMS | - | Energy Management System |
| HMI | - | Human Machine Interface |
| ICS | - | Industrial Control System |
| IPPs | - | Independent Power Producers |
| LAN | - | Local Area Network |
| LCC | - | Life Cycle Cost |
| MCAC | - | Maintained Cumulative Additional Cost |
| MoU | - | Memorandum of Understanding |
| MVA | - | Mega Volt Amps |
| NMD | - | Notified Maximum Demand |
| NPSH | - | Net Positive Suction Head |
| NWRS | - | National Water Resource Strategy |
| PEI | - | Pump Energy Indicator |
| PLC | - | Programmable Logic Controller |
| POR | - | Preferred Operating Region |
| SCADA | - | Supervisory Control and Data Acquisition |
| TBM | - | Time Based Maintenance |
| TOU | - | Time of Use |
| VSD | - | Variable Speed Drive |
| WAN | - | Wide Area Network |
| WC | - | Water Conservation |

WDM - Water Demand Management

WTP - Water Treatment Plant

## GLOSSARY

Consumer unit - a single point of delivery which receives one bill if the service is billed. A point of delivery receiving one bill can be a single household, a stand containing multiple households or even a block of flats.

# CHAPTER 1

Introduction

*Chapter 1*

*Chapter 1 introduces the water usage and the electricity usage of bulk water pumps in South Africa. A problem statement is formulated and the aim of the study is presented. The scope of the study is compiled and the layout of the dissertation is summarised.*

# 1 INTRODUCTION

The Department of Water and Sanitation (DWS) strives to provide all South Africans with access to clean water and safe sanitation. The department supports the management of water resources efficiently, ensuring sustainable economic and social development [1]. Water is seen as a critical element to ensure socio-economic development and to eradicate poverty [2].

The DWS (previously Department Water Affairs and Forestry) compiled a Water Conservation and Water Demand Management (WC/WDM) Strategy in August 2004.These strategies were set up for the water services sector as well as for the industry, mining and power generation sectors. Numerous opportunities exist in these sectors where these strategies can be applied/implemented. Water is a primary concern in South Africa, it is imperative that the opportunities to implement WC/WDM are pursued [3][4].

The WC/WDM strategy defines Water Demand Management as:

*"The adaption and implementation of a strategy by a water institution or consumer to influence the water demand and usage of water in order to meet any of the following objectives: economic efficiency, social development, social equity, environmental protection, sustainability of water supply and services and political acceptability."* [3]

The purpose of this study is to contribute to the economic efficiency of bulk water supply systems in South Africa. This will be achieved by quantifying the effect that decaying efficiency of a pump in a bulk water system has on the operational costs.

## 1.1 Water usage in South Africa

Figure 1 shows the four major water consuming sectors in South Africa. The largest water consumers by sector are: irrigation which accounts for 62% of the water usage in South Africa; domestic and urban use, accounting for 27% (which includes water for industrial use supplied by boards); mining, industry and power generation consumes 8% and; commercial forestry plantations consumes the remaining 3% [5].

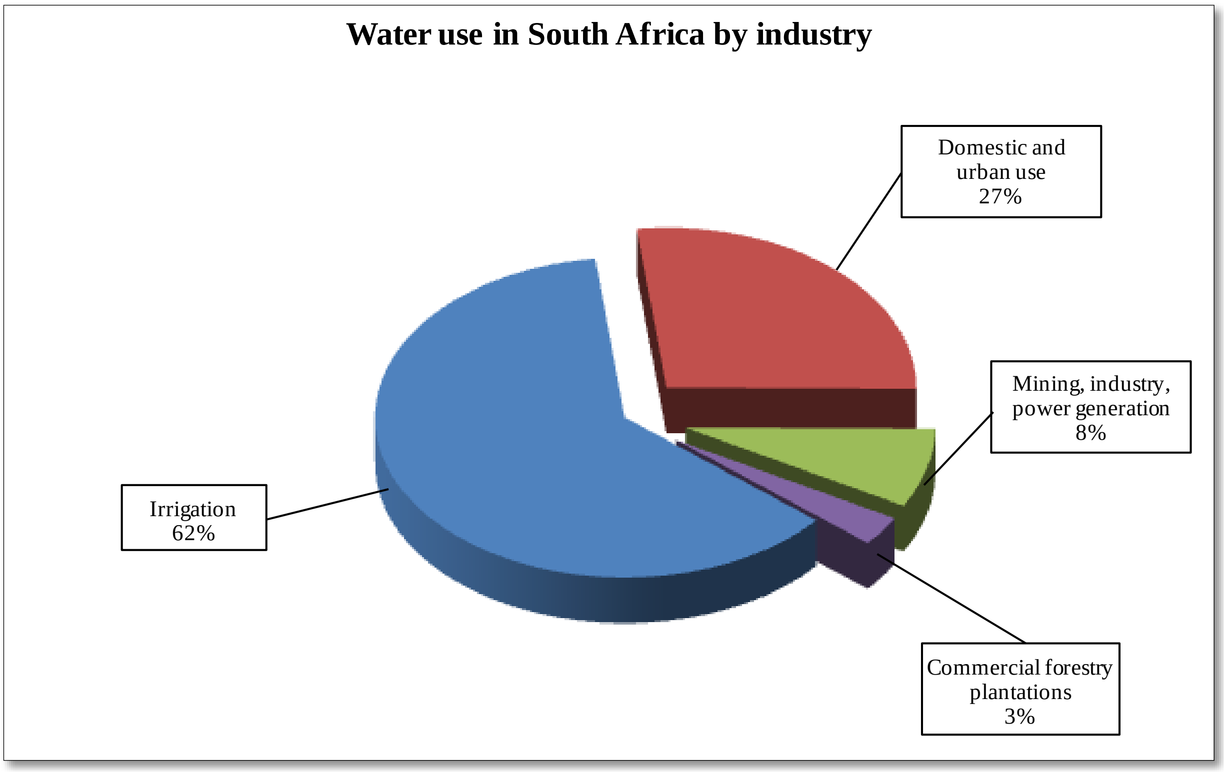


**Figure 1: Water use in South Africa (adapted from [5])**

It can be seen that by adding the water usage of domestic, urban, mining, industry and power generation, 35% of bulk water in South Africa, directly supplied by DWS, is allocated to these sectors.

A consumer unit is a single point of delivery which receives one bill, if the service is billed. A point of delivery receiving one bill can be a single household, a stand containing multiple households or even a block of flats.

According to Statistics South Africa, and shown in Figure 2, 11.8 million consumer units receive basic water [6]. The number of consumer units increased by 3.3% during 2012 and 2013 [6].

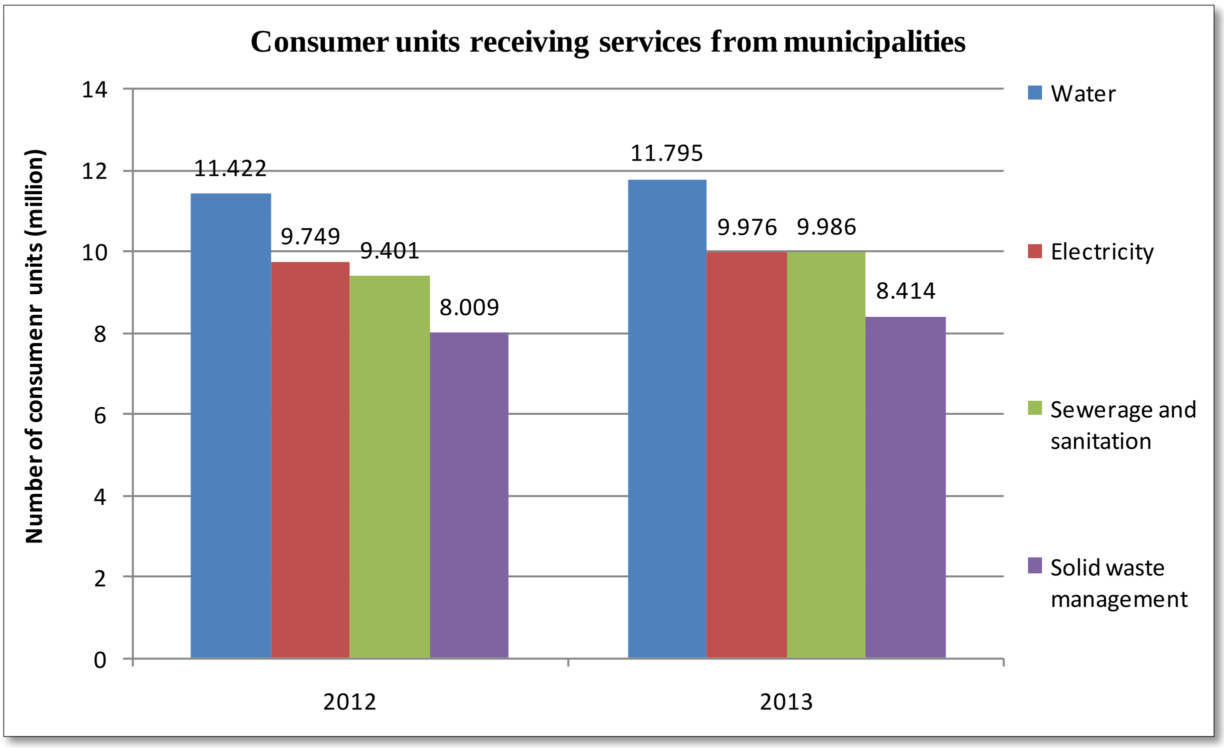


**Figure 2: Number of consumer units receiving services from municipalities: 2012 and 2013** (adapted from** [6]**)**

In 2013, the amount of consumer units receiving free basic water according to Statistics South Africa was 5.3 million. Considering the total amount of consumer units receiving water during the year of 2013, 44.7% benefited from free basic water [6]. It is imperative that the generated funds be effectively allocated to ensure continued operation and maintenance of water systems [7].

Of all the services delivered, as shown in Figure 3, water supply represents the highest percentage for consumers benefiting from the free basic services. The other basic services, including solid waste management, electricity, and sewerage and sanitation, have a 29.7%, 25.6% and 31.1% portion benefiting from the free basic services respectively [6]. Due to the high percentage of consumer units benefiting from free basic water, the need to deliver the water to them as efficiently as possible is crucial.

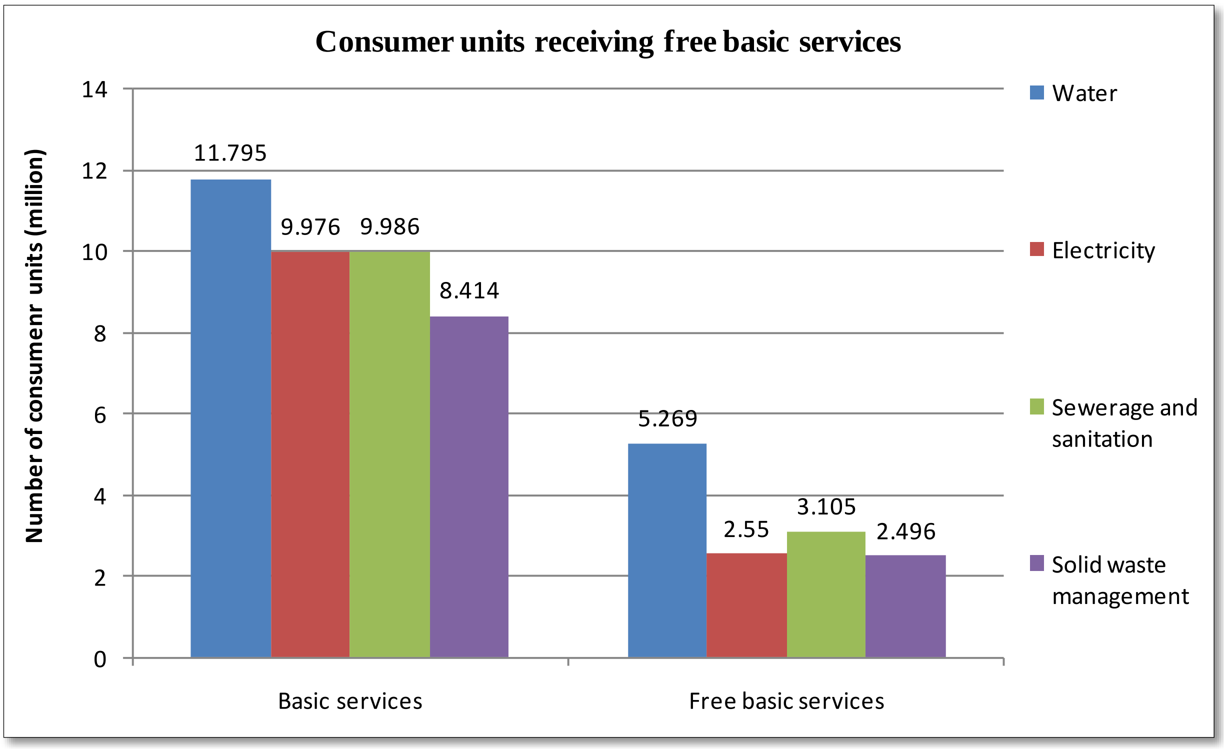


**Figure 3: Number of consumer units receiving basic services and free basic services: 2013** (adapted from** [6]**)**

Delivering treated water as opposed to untreated water increases the cost to DWS. In order for DWS to deliver bulk water to the municipalities effectively and cost efficiently, the equipment delivering the water has to be reliable and operate at its highest efficiency possible for as long as possible. This implies that the equipment should be monitored extensively and maintenance should be done as frequently as required.

## 1.2 DWS bulk water supply systems

DWS mainly supplies bulk water. The water supplied is either treated for human consumption or untreated. The bulk water is supplied to municipalities from where it is the responsibility of the municipality to distribute the water to the consumer unit. In the case where raw water is supplied to the municipality or end user, the bulk water supply system will include only the dam, raw water pump station, the rising main and a reservoir. A schematic view of a typical bulk water supply system is depicted in Figure 4.

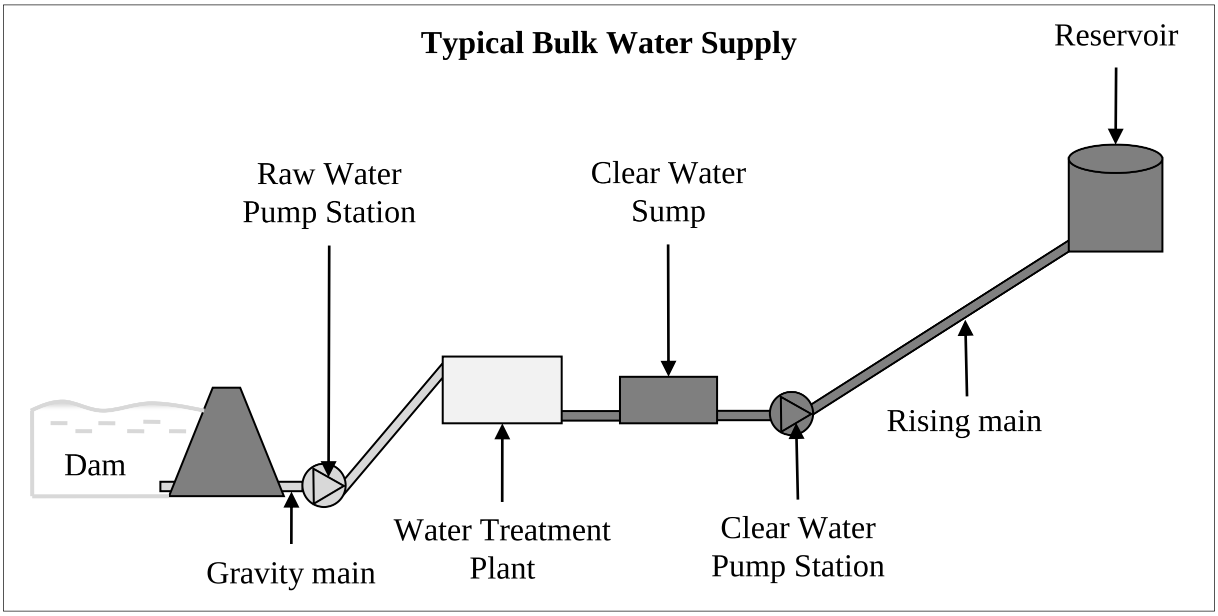


**Figure 4: Typical bulk water supply system**

Bulk water supply system pipe line diameters and lengths have a wide range. Pump station installed capacities range between several kilowatts to multiple megawatts. Taking these parameters into consideration, it is clear that the potential exists where hundreds of thousands of Rands can be wasted in operational costs if these pump stations are not maintained and operated effectively and efficiently.

Multiple factors in a bulk water supply system can prevent the system from delivering the water effectively and cost efficiently. Factors that cause inefficiencies in the system are:

- Incorrect installation of pipelines;
- Aging pipelines that result in an increase in pipe roughness;
- Leaks;
- Incorrect installation of valves;
- Incorrect operation of valves;
- Incorrect installation of pumps;
- Incorrect operation of pumps.

More factors that cause inefficiencies in these systems exist and can be found in literature. Managing these inefficiencies poorly will result in wasting vast amounts of money.

## 1.3 Electricity usage by bulk water pumps in South Africa

In bulk water supply systems, the only objective of the pump station is to transport the water via pumps. The electricity demand of the pumps in pump stations will be greater than 90%. The electricity demand of pumps in certain other industrial plants range from 25%-50% [8].

### 1.3.1 Bulk water systems supplying water to Eskom

Eskom accounts for approximately 2%-3% of the total water consumption in South Africa [9]. Eskom entered into an agreement with the DWS to pay for a portion of the operational costs incurred by DWS on certain water schemes [10]. Certain pump stations in the water schemes of DWS are operated and maintained by Eskom resources[1]. Eskom pays a portion of the operational and maintenance costs from which they receive water for use in power stations.

Eskom is classified as a Strategic Water User under the National Water Resource Strategy (NWRS). This classification is due to the strategic role of electricity in the development of the country and its economy. Due to the strategic role of electricity in South Africa, DWS supplies Eskom with water at a 99.5% assurance level. A 99.5% assurance level requires that water be supplied to Eskom with a risk of failure of 1 in 200 years [9].

The previous minister of the Department of Water Affairs and Forestry (currently DWS), Lindiwe Hendricks and the chief executive of Eskom, Jacob Maroga, signed a Memorandum of Understanding (MoU) in 2008. The MoU established a strategic partnership that encourages efficient and sustainable water usage at Eskom's power stations [11].

Using water efficiently reduces the amount of water needed for a specific process which reduces the amount of electricity needed to pump the water. However, this efficient use of water does not eliminate the need for electricity savings in pumping costs. The demand for monitoring and maintaining pumps in order to maintain their efficiency as close as possible to their installed efficiency subsist.

---

[1] Verbal communication with Jan-Paul Spangenberg from HVAC International (Pty) Ltd on 19 January 2016.

In January 2008, a national emergency was declared on the Eskom power supply in South Africa. Since then Eskom has initiated a recovery plan and the power system has been stabilised significantly. Eskom introduced new capacity to the grid and stockpiles were rebuilt. A programme named Demand Side Management (DSM) was implemented which has achieved savings in electricity usage and Eskom also bought capacity from Independent Power Producers (IPPs) [12].

### 1.3.2 Bulk water systems supplying water to the public

As shown in Figure 5, water infrastructure consumes 3% of the electricity in South Africa. Distribution of water to the end user requires pumps and pumps consume electricity. These pumps include bulk water distribution system pumps managed by DWS and water boards, as well as pumps in distribution systems managed by municipalities.

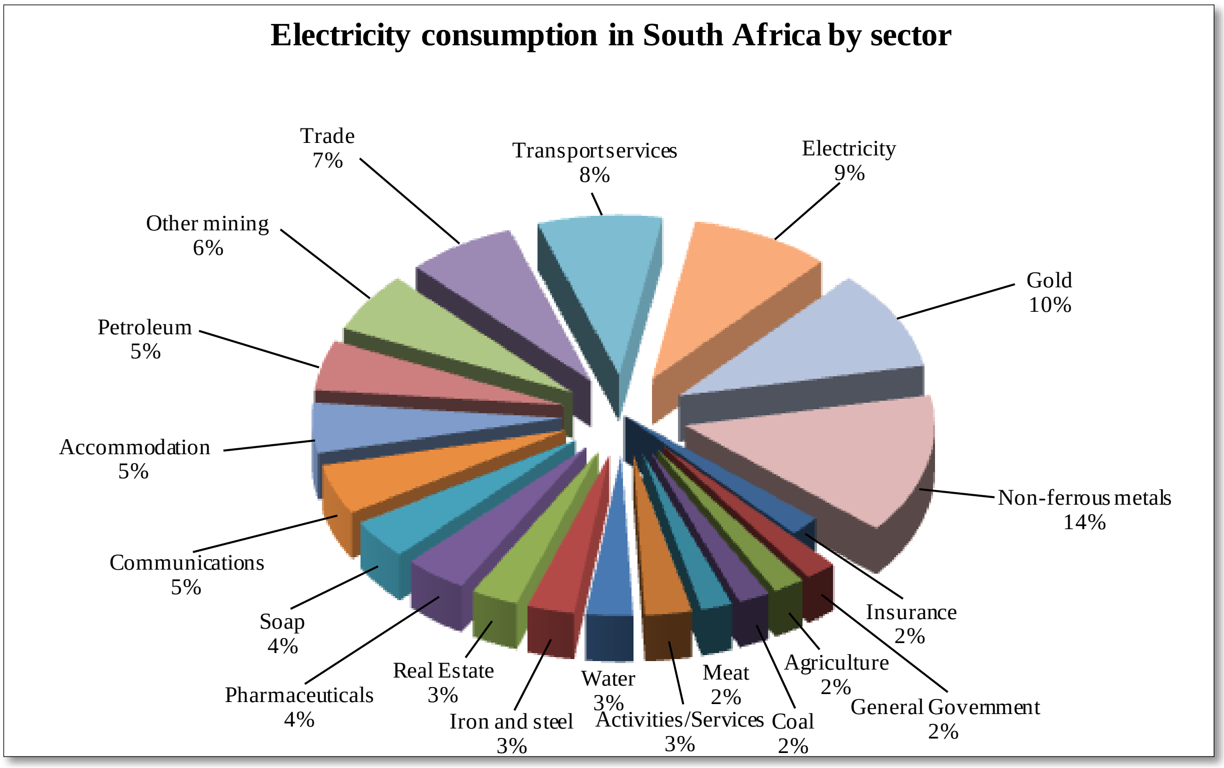


**Figure 5: Electricity consumption in South Africa by sector (adapted from** [13]**)**

A substantial amount of the electricity used in South Africa by sector, shown in Figure 5, is allocated to industrial sectors including:

- Iron and steel 3%;
- Pharmaceuticals 4%;
- Soap 4%;
- Petroleum 5%;
- Mining combined 16%;
- Non-ferrous metals 14%[13].

Each of these industrial activities make use of pumps, ventilation fans, compressed air etc. Electrical motors in industry consumes approximately 60% of South African supplied electricity whereas pumps account for the largest load [14].

### 1.3.3 Effect of energy on the Life Cycle Cost

The typical Life Cycle Cost (LCC) of a pump system, over a period of 7 years, is depicted in Figure 6 [15].

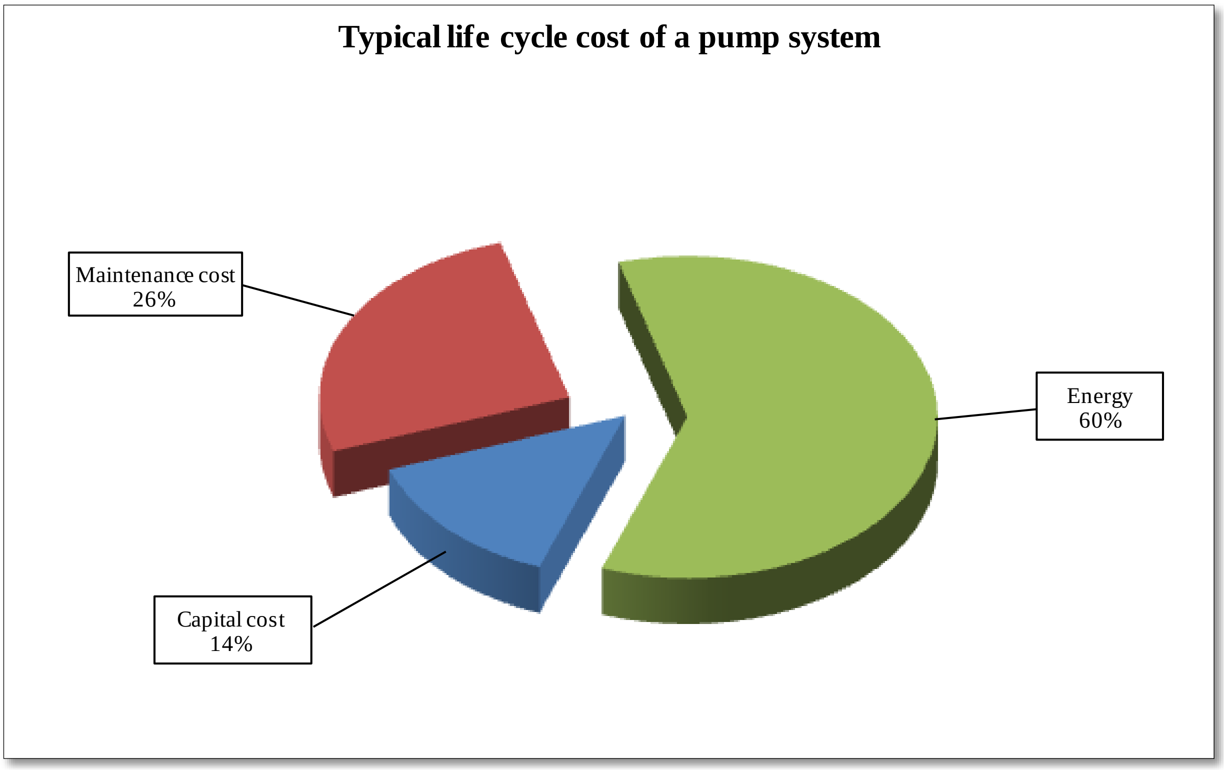


**Figure 6: Typical life cycle cost of a pump system (adapted from** [15]**)**

For the seven year life cycle time of the specific pump depicted in Figure 6, the typical energy cost of the pump system accounts for approximately 60% of the LCC. Maintenance costs account for approximately 26% of the LCC. The initial capital costs account for a mere 14% of the LCC. Increasing the life cycle time in the LCC calculation will increase the energy and maintenance portion of the total LCC and decrease the overall percentage of the initial capital cost. The LCC of different types of pumps differ [15].

Maintaining a pump frequently and effectively will ensure that the average efficiency of the pump remains as high as possible. Operating a pump efficiently consequently lowers pumping LCC. Operating a pump inefficiently can affect the mechanical reliability of the pumping system, ultimately compromising service delivery. Pump failure in a bulk water supply system can cause additional costs to the LCC of a pump system. This additional cost is called production losses [16].

Eskom uses a time of use (TOU) tariff structure and clients are billed according to this structure. The structure is divided into low demand season and high demand season. The respective seasons are divided into weekdays, Saturday and Sunday, and a day is divided into peak, standard and off-peak periods. Between the low demand season and the high demand season, the only difference is the time of the peak period. The peak period is shifted one hour earlier in the high demand season. The amount of peak, standard and off-peak periods remain the same in both the high and low demand seasons. A more detailed description of the TOU structure is given in Chapter 3 of this dissertation.

The result of production losses in a bulk water supply system is a shortage of water to the end user. After the problem that caused production losses is restored, catching up on production is required. This may require operating the pumping system over an extend period of time through the standard, peak and off-peak energy charge timeslots. Operating in the standard and peak energy charge timeslots accounts for unwanted costs that contribute to the production losses cost in the LCC calculations. Ultimately it can be said that the production losses factor of a LCC calculation can be included in the energy portion of the costs of a bulk water supply system.

## 1.4 Advantages of monitoring pump efficiency

Allowing the efficiency of a pump to decrease below its initial manufactured/installed efficiency results in unnecessary power usage and operational costs. Monitoring efficiency is a method of knowing what the operational status of the pump is. Corrective procedures will have to be carried out on the pump in order to maintain the efficiency of the pump so it can be as close as possible to its original efficiency. Figure 7 shows the average wear trends for maintained and unmaintained pumps.

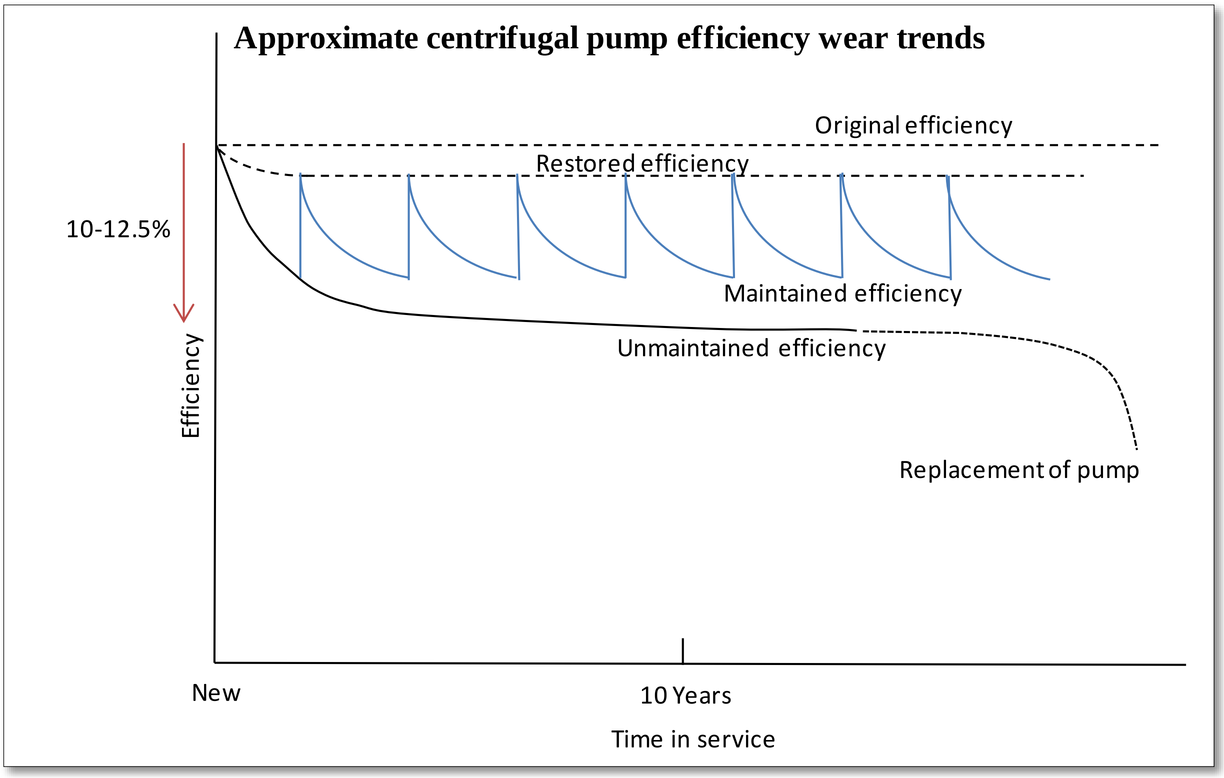


**Figure 7: Approximate efficiency wear trends for maintained and unmaintained pumps (adapted from** [17]**)**

Maintaining the pump regularly keeps the average lifetime efficiency of the pump relatively close to its original efficiency as seen in Figure 7. Shortening the maintenance intervals increases the average pump efficiency. Maintaining a high average pump efficiency reduces the energy consumption and increases service delivery. The efficiency however, cannot be completely restored to its original efficiency through normal regular maintenance procedures. Restoring the pump to its original efficiency would require that all the pump's original fits and tolerances be restored [18].

Monitoring the efficiency of a pump adds to the benefit of detecting problems. Early detection of problems within the pump adds to the advantage of being able to plan for repairs and avoid early pump failures. Losses in pump efficiency and capacity can occur long before pump failure [17]. Keeping the pump in a well maintained state ensures that the demand expected from the pump is sustained.

Maintaining the efficiency of a pump will improve environmental outcomes through a lower demand for electricity which results in less carbon emissions due to energy generation [17].

## 1.5 Problem statement and aim of study

### Problem statement

Across the majority of bulk water pump stations in DWS, the most common maintenance methodology is either time based maintenance (TBM)(also known as preventative maintenance) or run-to-fail. The most common reason for the use of run-to-fail maintenance at specific pump stations is due to a lack of funding and/or a shortage in manpower.

Most equipment suppliers include a maintenance plan with the sale of their equipment. This maintenance plan is usually a TBM plan. The TBM plan is not the most effective and efficient maintenance plan as the equipment does not always operate in the standard conditions. Also, the supplier may have hidden agendas in maximising the turnaround of their spare parts with the supplied equipment [19].

Another maintenance methodology is condition based maintenance (CBM), also known as predictive maintenance. CBM is a maintenance method in which the condition of the equipment is constantly monitored and corrective actions are based on the collected information.

If a poor maintenance methodology is incorporated in bulk water supply systems, the unnecessary additional operating costs may become a substantial amount considering the installed capacity of the pump station. The deterioration rate of a pump can be coupled to the deterioration rate of the pump's efficiency. Currently the efficiency of bulk water pumps within DWS is not monitored continuously. The effect of a deteriorating efficiency within a bulk water pump on operational cost is unclear.

All the data collected from the DWS pump stations were manually filled by the operator. The data were of poor quality and no maintenance data of any of the pumps in the study could be obtained. Due to the poor quality of the data obtained it is needed to determine if the available data could be used to determine the operational performance of the pump sets.

**Aim of study**

The aim of the study is to:

- Evaluate the accuracy and availability of operational data to evaluate performance,
- Quantify the unnecessary additional operating costs by calculating the efficiency decay of the pumps in bulk water distribution systems,
- Quantify/illustrate the effect of increasing the efficiency of the pump by doing regular maintenance based on the predefined magnitude of the efficiency decay.

## 1.6 Scope of study

The scope of this dissertation will only focus on **bulk water pump stations** from DWS. It is also assumed that the pipe roughness remains constant throughout the study.

Numerous factors, other than pump efficiency, exist in a bulk water system that could have a negative effect on the efficiency of the system. These factors are not considered in this dissertation. These factors are assumed to remain constant throughout the study. The main focus of this dissertation is the effects that decaying pump efficiency has on the operating costs of the bulk water system.

A pump set consists of an electrical motor that drives the pump via coupling that connects the two pieces of equipment. The measured power input to the system is directly supplied to the motor. The power supplied to the fluid is a function of the total power input, motor efficiency and pump efficiency. For this study, the efficiency calculated will be the efficiency of the pump set which is a product of the motor efficiency and the pump efficiency.

This dissertation will only focus on a specific type of pump, namely **centrifugal pumps**.

## 1.7 Layout of the dissertation

Chapter 1: Introduction

Chapter 1 introduces the water usage and the electricity usage of bulk water pumps in South Africa. A problem statement is formulated and the aim of the study is presented. The scope of the study is compiled and the layout of the dissertation is summarised.

Chapter 2: Operation and maintenance of centrifugal pump sets

In Chapter 2 the relevant literature on what causes the efficiency of a pump system to decrease is evaluated. Chapter 2 also determines what can be done to improve the efficiency of a pump system and by how much the efficiency can be improved by making use of a suitable monitoring system and maintenance procedures.

Chapter 3: Energy consumption analysis of pump stations

The method of obtaining data is presented. The calculation of the efficiency of each pump set is described, as well as how the efficiency decay is predicted. The method used to calculate the energy cost for a pump set is described.

Chapter 4: Assessment of energy consumption results

In Chapter 4 the four case studies which consist of fourteen individual pump sets are presented. The effect of maintaining a relatively high pump set efficiency is illustrated for each individual pump set.

Chapter 5: Conclusion and recommendations

Chapter 5 concludes this dissertation and discusses recommendations for further studies.

# CHAPTER 2

## Operation and maintenance of centrifugal pump sets

*Chapter 2*

*In Chapter 2 the relevant literature on what causes the efficiency of a pump system to decrease is evaluated. Chapter 2 also determines what can be done to improve the efficiency of a pump system and by how much the efficiency can be improved by making use of a suitable monitoring system and maintenance procedures.*

# 2 OPERATION AND MAINTENANCE OF CENTRIFUGAL PUMP SETS

## 2.1 Introduction

This chapter will focus on centrifugal pumps, how they work and what causes the decrease in their efficiency. Fundamental basics concerning induction motors are given, as well as the factors causing a decrease in the efficiency of an induction motor. Literature on monitoring systems and how they are used to detect the state of the pump making use of predefined limits are analysed.

Failure modes of pumps and corrective procedures that will lead to an increase in the efficiency of the pump are considered. Maintenance structures and how they are used on pumps are reviewed. Finally, a comprehensive literature survey focusing on what savings in operational costs can be realised in the case of maintaining the efficiency of a pump system are presented.

## 2.2 Centrifugal pumps and induction motors

### 2.2.1 How a centrifugal pump works

A centrifugal pump is a very simple piece of equipment and the basic purpose of a centrifugal pump is to convert energy that it receives from, most commonly, an electrical motor into kinetic energy and finally into pressure energy of the fluid it pumps. A centrifugal pump comprises of six main parts which includes an impeller, bearings, bearing frames, seals, a casing and a shaft. This can be seen in Figure 8, which shows a detailed cutaway of a commonly used centrifugal pump in bulk water systems [20][21][22].

The conversion of energy is caused by two main parts of the pump, the impeller and the diffuser, of which the impeller is the rotating part and the diffuser the stationary part. The impeller converts the mechanical energy into kinetic energy by creating a centrifugal force on the fluid causing the fluid to accelerate outwards towards the tips of the impeller vanes. The vanes of the impeller are usually curved which, together with the centrifugal force, pushes the fluid in a tangential and radial direction [21].

The fluid leaving the impeller enters the casing volute which creates resistance and slows down the fluid which in turn converts the kinetic energy to pressure energy. From the volute the fluid enters the diffuser which slows down the fluid further and continues to convert the kinetic energy to pressure energy. The energy conversion follows the Bernoulli principle which states that the total energy entering the system should equal the total energy leaving the system plus a loss term [23][21].

Figure 8 shows a detailed description of the components of a horizontal split casing centrifugal pump. The six main components can clearly be seen. Some components may vary from different models of centrifugal pumps. For instance, the roller bearings of the pump in Figure 8 can be replaced by white metal bearings. The gland packing seal of the pump can be replaced by mechanical seals. In each case the specific pump should be analysed and a detailed assembly drawing of the pump should be obtained to know the construction of the pump.

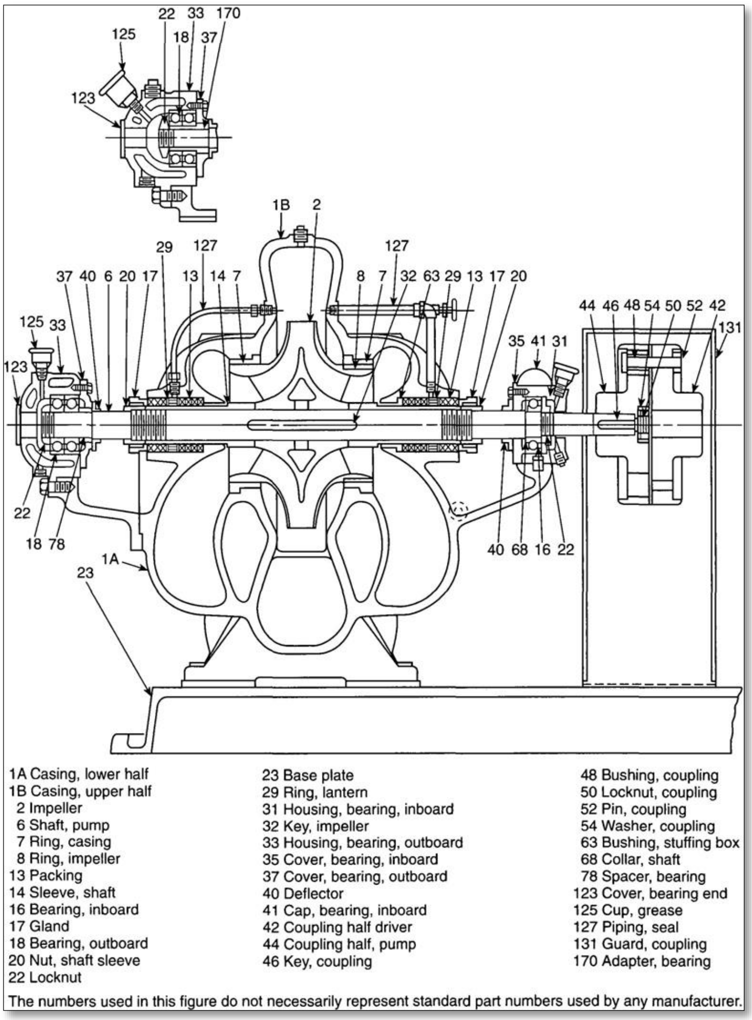


**Figure 8: Detailed description of the parts of a horizontal split casing centrifugal pump [20]**

The kinetic energy that is developed by the rotating impeller, measured in metres height of the liquid, is approximately equal to the velocity energy at the periphery of the impeller. This energy is expressed by the following formula:

$$H = \frac{V^2}{2g} \text{ [21]}$$

Where:

H - total head developed in metres

V - velocity of the fluid at the periphery of the impeller in m/s

g - gravitational acceleration 9.81 m/s$^2$

The peripheral velocity of the impeller is calculated using the following formula:

$$V = \frac{\pi}{60} ND \text{ (adapted from [21])}$$

Where:

V - velocity of the fluid at the periphery of the impeller in m/s

N - impeller rotational speed in rpm

D - impeller diameter in metres

An ambiguous and difficult to evaluate parameter for a centrifugal pump is known as the specific speed. The specific speed of a centrifugal pump is calculated as follows:

$$N_s = \frac{N\sqrt{Q}}{H^{3/4}} \text{ [24]}$$

Where:

$N_s$ - pump specific speed index number

N - impeller rotational speed

Q - flow rate

H - total head developed

A correlation exists between the pump specific speed and the geometry of the pump impeller. It can be said that a low specific speed value is associated with a high generated pump head assuming that the rotational speed and flow rate remains constant. In opposition, a high specific speed value is associated with a low generated pump head assuming that the rotational speed and flow rate remains constant [24].

A graphical representation of the correlation between specific speed and impeller geometry is shown in Figure 9. Specific speed values shown in Figure 9 are derived from British units and the use of metric units will result in different specific speed values that are not comparable with these units [24].

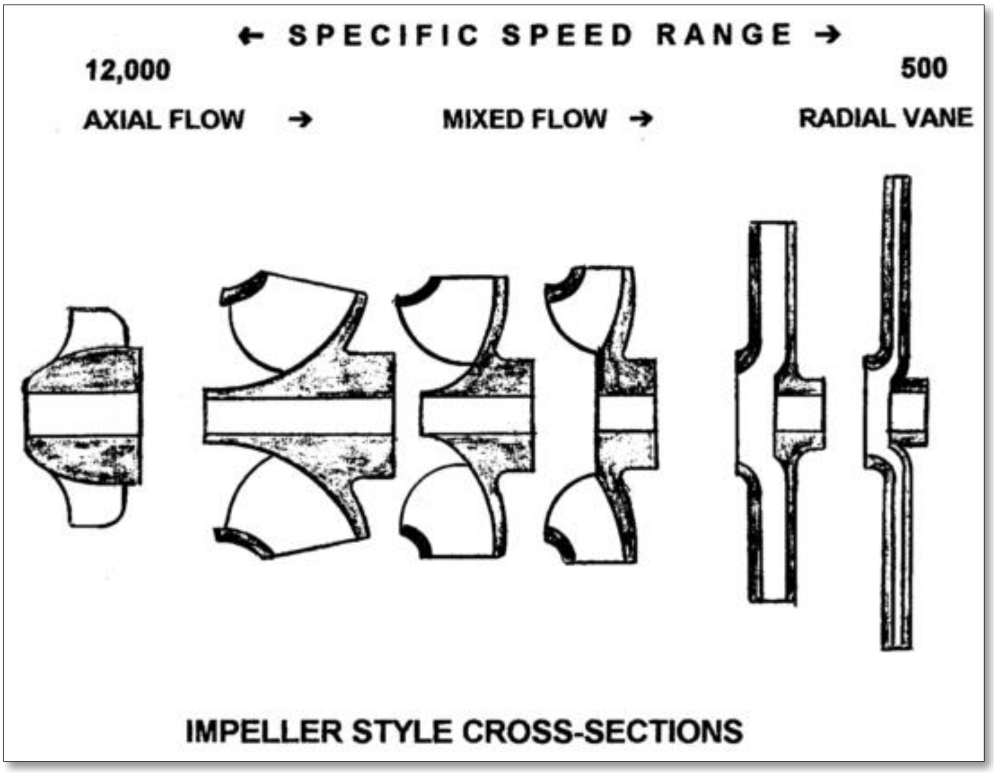


**Figure 9: Correlation between specific speed and impeller geometry** [24]

The specific speed influences the efficiency of a centrifugal pump. This phenomenon is discussed in detail in Section 2.2.2 and shown in Figure 12.

### 2.2.2 Factors influencing the efficiency of a centrifugal pump

There are two main factors that influence the efficiency of a centrifugal pump. These are operational factors and mechanical factors. Both factors, operational and mechanical, can be controlled either by doing maintenance on the pump or correct operation of the pump. By implementing correct maintenance or operation of the pump, the efficiency can be held relatively high and close to the initial best efficiency point (BEP) at which the pump is designed to operate in its unique situation.

There are currently two methods of testing a pump's efficiency as stated by Fabian Papa & Djordje Radulj [25]. These methods are: conventional and thermodynamic. Both methods, when applied correctly and under the correct conditions, are reliable and yield accurate results. However, due to the configuration of pipes around the pumps, the situations are usually not ideal for certain measurements such as flow.

In both methods, conventional and thermodynamic, the power input is measured as well as the differential pressure across the pump. In the conventional method, the flow through the pump is measured and the efficiency is calculated. The thermodynamic method on the other hand measures the temperature gain of the fluid across the pump which is a direct measure of the amount of energy lost, that is the inefficiency of the pump [25].

Due to the nature of the available data obtained in this research, the conventional method of calculating the efficiency of a pump was used.

### Operational factors influencing the efficiency of a centrifugal pump

The first operational factor influencing the efficiency of a centrifugal pump is selecting the correct type of centrifugal pump for the specific application. Budris [26] stated that according to the specific application for the pump, the pump will need to be designed specifically for this application. Design considerations such as handling large solids, fluid temperature and viscosity should be taken into consideration when selecting a pump [26].

Operating too far from the BEP causes the pump to operate at a low efficiency. It also causes imbalanced forces within the pump as shown in Figure 10. These imbalanced forces cause excessive wear of parts. It is good practice to operate a pump between 80% and 110% of the BEP. Operating far to the left of the BEP causes operational problems.

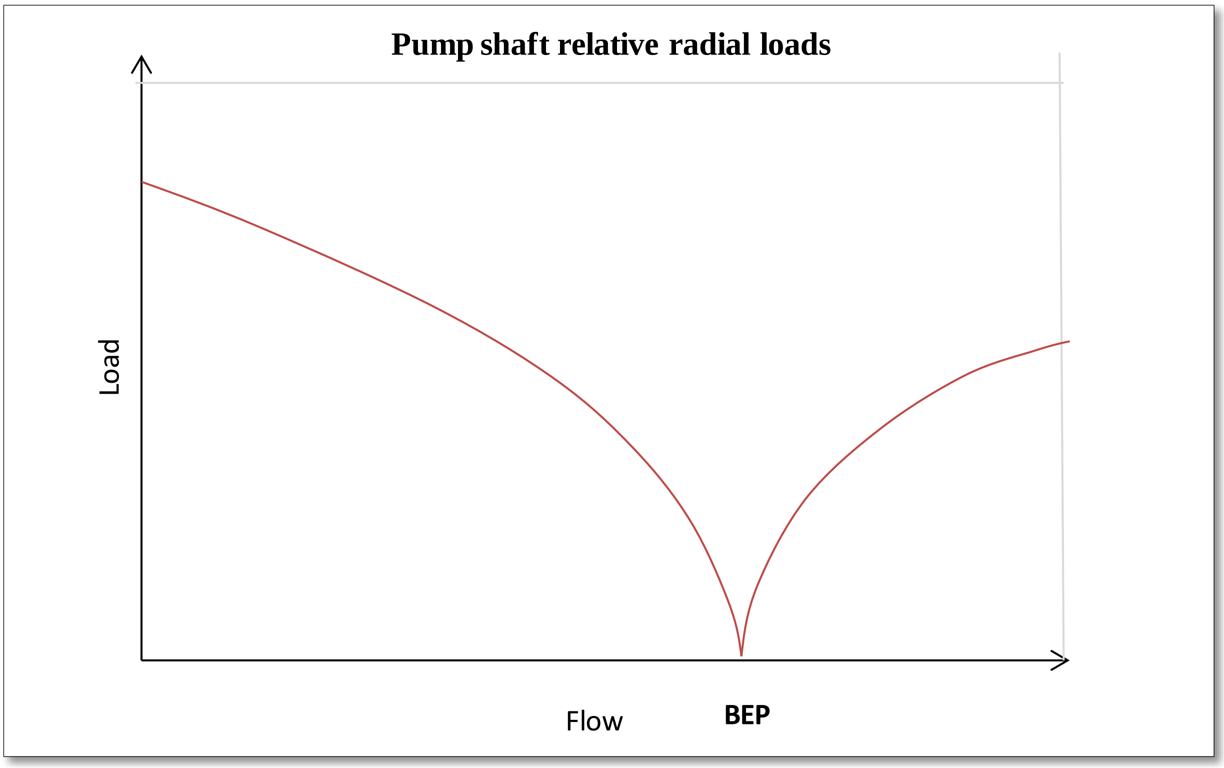


**Figure 10: Pump shaft relative radial load vs. flow (adapted from** [27]**)**

Figure 11 shows operational problems when a centrifugal pump is operated too far away from its BEP [22]. The operating regions of a pump can be divided into two regions where the pump will have a long pump life and stable operation. These two regions are named Preferred Operating Region (POR) and the Allowable Operating Region (AOR). Both the operating ranges influence the efficiency of the pump [27].

The POR is defined as the more restrictive operating range of the pump where the flow is uniform and free from separation. The range of operation from the BEP for most centrifugal pumps, according to standards, is between 70% and 120%. For certain axial flow pumps the POR is narrower, 80% to 115% of the BEP flow. Operating the centrifugal pump within the POR will ensure smooth operation and the pump will last its intended service life and ensure good operating efficiency [27][22].

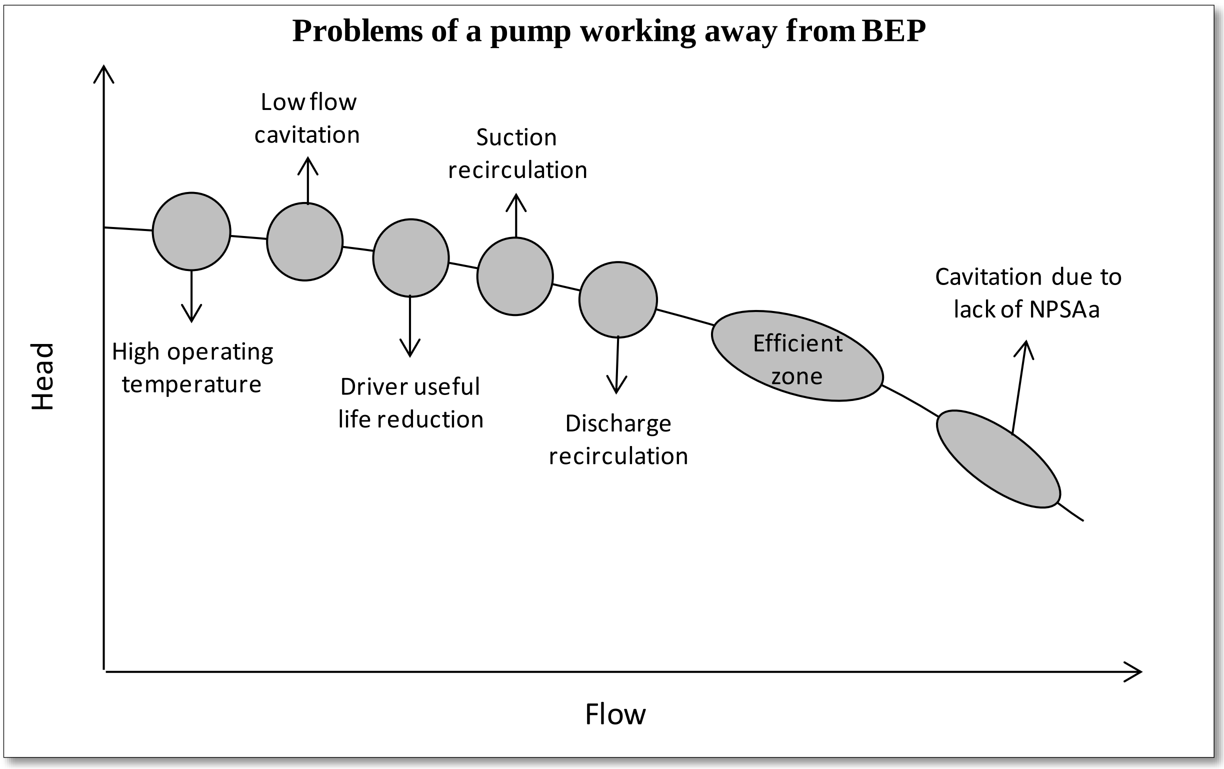


**Figure 11: Problems of a pump working away from BEP (adapted from** [28]**)**

The AOR defines a wider operating range than the POR. The AOR, as determined by the pump manufacturer, is the range where the pump service life is not reduced significantly compared to a similar pump operating in the POR. In this operating region the risk for unfavourable conditions is greater than within the POR. Unfavourable conditions such as noise, vibration, increase in temperature and increased shaft loading are results of operating in the AOR. These unfavourable conditions cause the pump to operate at a lower efficiency [27].

Installing any size and type of pump correctly ensures successful operation and maintenance of the pump. Correctly installed pumps are aligned to specification which result in lower vibration and lower risk of leaking casings and flanges. Correctly installed pumps remain aligned to specification for a longer period of time which increase the service life of the pump [29].

The specific speed of a centrifugal pump, as described in Section 2.2.1 influences the efficiency of the pump. Figure 12 shows how the efficiency is influenced by the specific speed. It can be seen that the maximum BEP obtainable by centrifugal pumps is within the specific speed range of 2000 to 3500.

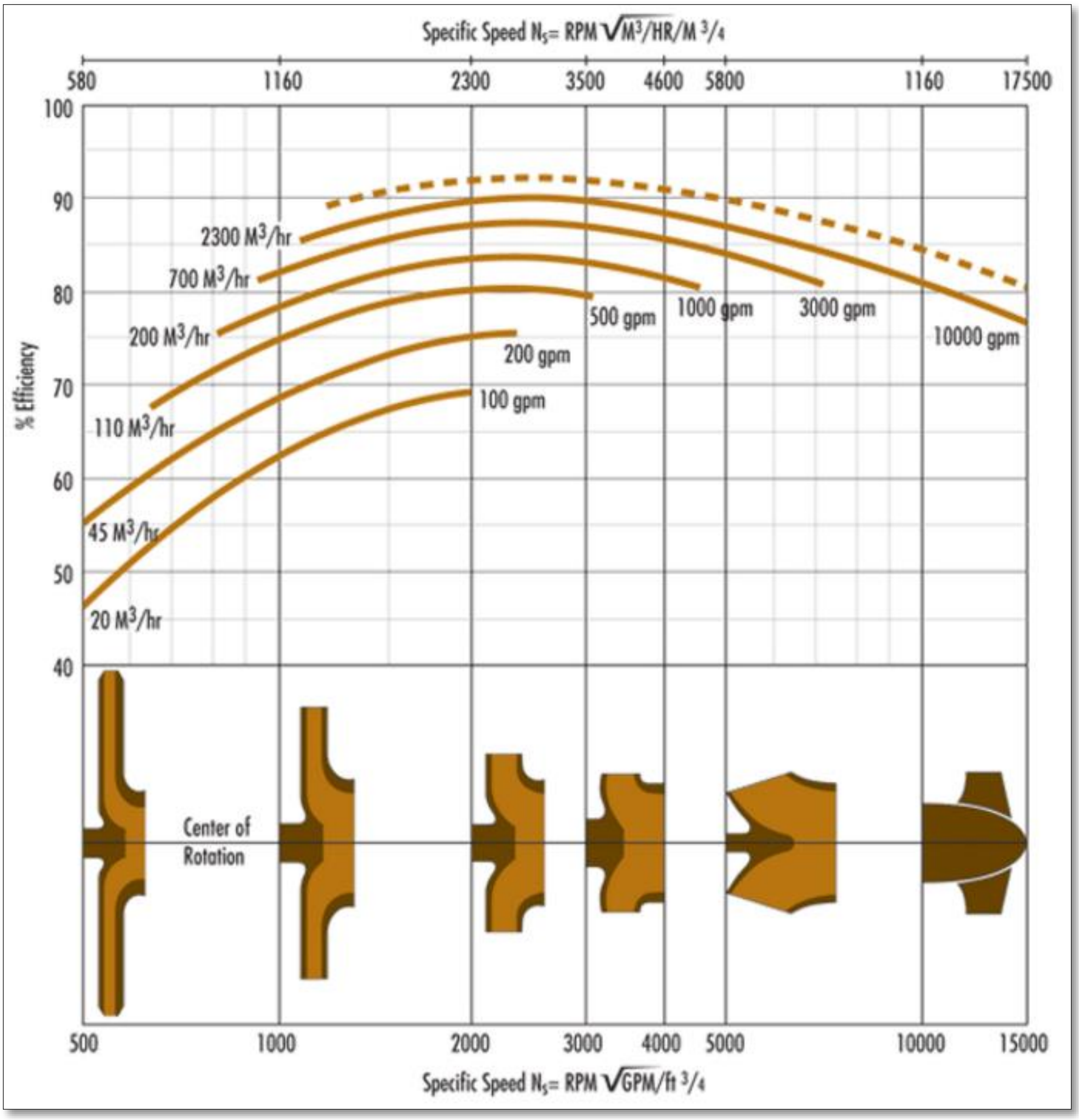


**Figure 12: Impact of pump specific speed on the efficiency** [26]

By changing the pump rotational speed, the required flow rate or the head, the efficiency of the pump can be altered towards or further away from its BEP. In the case that an application calls for a low specific speed, which result in a low efficiency, impellers can be added to the pump which in turn reduces the head produced by each impeller. This reduction in head produced by each impeller increases the specific speed which moves the pump closer to its BEP [26].

Specific plants require a specific flow rate for the required process. The flow rate can be controlled via a control valve which opens or closes according to feedback from the flow sensor. The flow rate can also be controlled by changing the rotational speed of the pump. The rotational speed can be changed by making use of a Variable Speed Drive (VSD) which alters the frequency at which the electrical motor operates.

Another method of changing the rotational speed of the pump was tested by YouFang Liu [30] and was found to be just as effective. The method is named Permanent Magnetic Speed Control in which the coupling between the motor and pump is realised by a variable magnetic field [16].

Figure 13 shows the effect that throttling and speed change have on the power consumption when a change in flow rate needs to be made. It is clearly shown that throttling decreases the power consumption by 0.5 kW (7%), but changing the operational speed to obtain the same reduced flow rate reduces the power consumption by 3.5 kW (50%). Correspondingly, when reducing the operational speed of the pump, the BEP of the pump shifts with the reduction in speed. Resultantly, not only does the power consumption reduce, but the pump will operate at a higher efficiency at a reduced speed than when the flow is reduced by throttling.

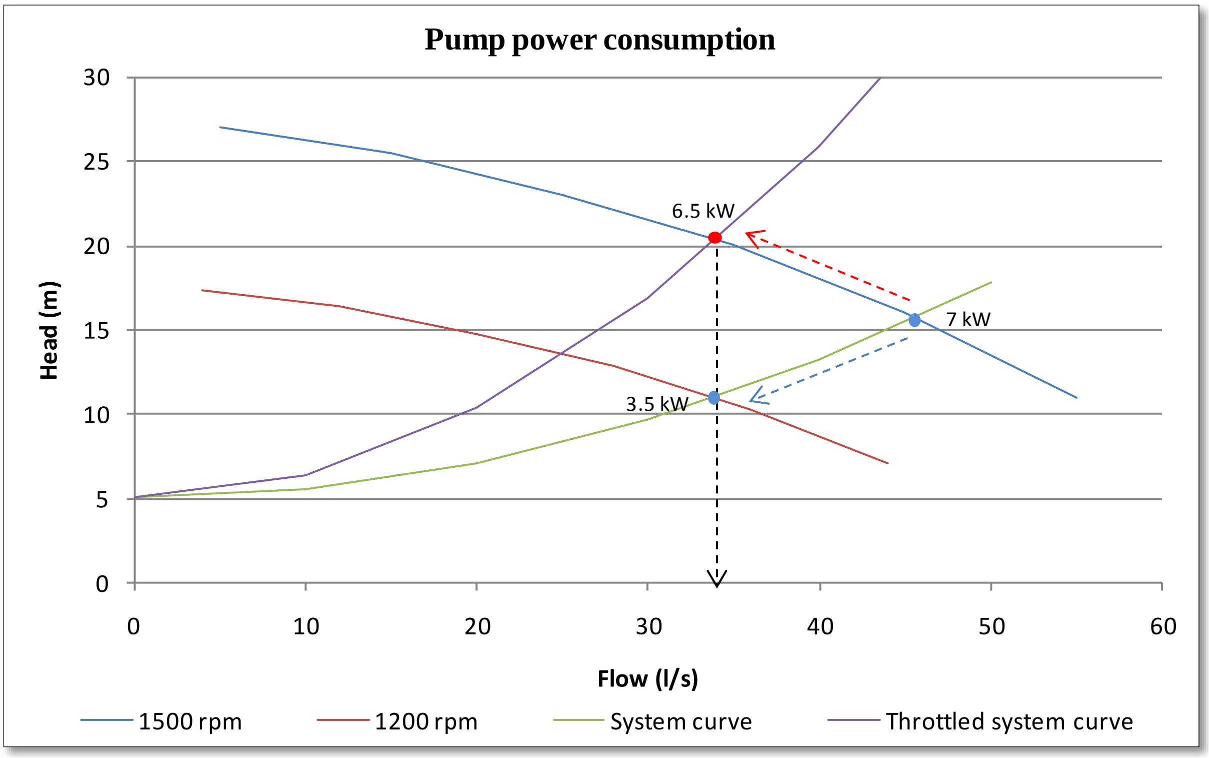


Figure 13: Power consumption: throttling vs. rotational speed change

**Mechanical factors influencing the efficiency of a centrifugal pump**

Viscous drag within the pump causes a loss in pressure across the pump and ultimately decreases the efficiency of the pump. In the Journal "World Pumps" by Beck [18], the internals of the pump and the impeller was coated with a ceramic coating. The coating applied is hydrophobic and creates a very smooth surface resulting in very low friction losses across the pump, which ultimately increases the efficiency of the pump. A study was completed by the Monroe Country Water Authority, in collaboration with the New York State Energy and Research Development Authority, and the results showed that in most of their research cases the efficiency of a pump was increased by 5% -10% after coating the internals of the pump with the ceramic coating [18].

**Figure 14: Pump casing and impeller after ceramic coating** [18]

The efficiency of a pump can be increased through renewal of its original tolerances and fits. The main component usually causing efficiency decay in a pump due to increasing tolerances are the wear rings. Increasing the tolerance of the wear rings, due to operational wear, results in excessive leakage of the pumped fluid from the high pressure zone (discharge) to the low pressure zone (suction) within the pump. This phenomenon causes a reduction in the net flow from the pump and ultimately a decay in the efficiency of the pump. According to Beck [18], it was found that when reducing the clearances by 50%, the efficiency gain by this specific process pump could range from 4% -5% [18].

Misalignment of pumps cause the following mechanical problems, which in turn affects the efficiency of the pump negatively:

- Overload of the pump bearings;
- Unfavourable movement of the mechanical seal decreasing the life of the seal and increasing the possibility of leakage;
- In case of severe misalignment, contact between rotating and stationary components;
- Contact between the wear rings;
- Contact between the volute and impeller [29].

Misalignment of pumps can also be caused by thermal effects on the materials of the pump and motor. To calculate the thermal growth of the pump, or even the motor or piping, is very difficult. These thermal effects create unpredictable movement within the system which cause misalignment. Removal of the coupling almost always results in a degree of misalignment when reinstalled. Misalignment caused by thermal effects, or due to removal and replacement of the coupling, will result in the mechanical problems mentioned in the previous paragraph. These mechanical problems ultimately influence the efficiency of the pump [31].

Faulty pump bearings have a significant impact on the efficiency of the pumping system. Research done by Abu-Zeid [32], focused on the effect that damaged rolling element bearings have on the performance of pumping stations. His research proved that damaged bearings generates forces which cause vibrations that result in increased energy consumption. Abu-Zeid found in his research that replacing faulted bearings can have a significant decrease of 10% -14% in the electric power consumption. The overall pump efficiency can increase by up to 18% after replacing a faulted bearing [32].

### 2.2.3 How an induction motor works

The induction motor, also known as the asynchronous motor, is the most popular and most rugged motor used in DWS pump stations. The most widely used design for the induction motor is the squirrel cage design. The induction motor has two major components. The stationary component known as the stator, and the rotating component known as the rotor [33].

The stator component is manufactured out of laminations of high grade sheet steel, which is slotted on the inner side to accommodate the three pairs of windings. The rotor component is manufactured out of slotted laminations of a ferromagnetic material. The slots are then filled with bars which are either copper or aluminium. The bars are then coupled at the ends by means of end rings [34].

Applying a three-phase voltage to each of the three winding phases in the stator creates a revolving magnetic field. The three phases of the revolving magnetic field are out of phase by 120 degrees. The stator and the rotor are separated by an air gap and there is no electrical connection between the stator and the rotor. The magnetic field from the stator induces a current in the rotor. The rotor is then magnetised due to the induced currents. The coupling between the stator and the rotor is then achieved with the rotating magnetic field [33][34].

**Figure 15: Induction motor cutaway showing the stator and rotor** [33]

### 2.2.4 Factors influencing the efficiency of an induction motor

Electrical motors are major consumers of electricity in the industrial sector. In pump stations from DWS, electrical motors account for over 90% of the electricity consumed. The most commonly used electrical motor in DWS pump stations is the squirrel cage induction motor (asynchronous motor). There are multiple factors in induction motors that cause efficiency losses. Figure 16 shows the typical energy losses within standard induction motors. The losses are given in percentage of the total losses.

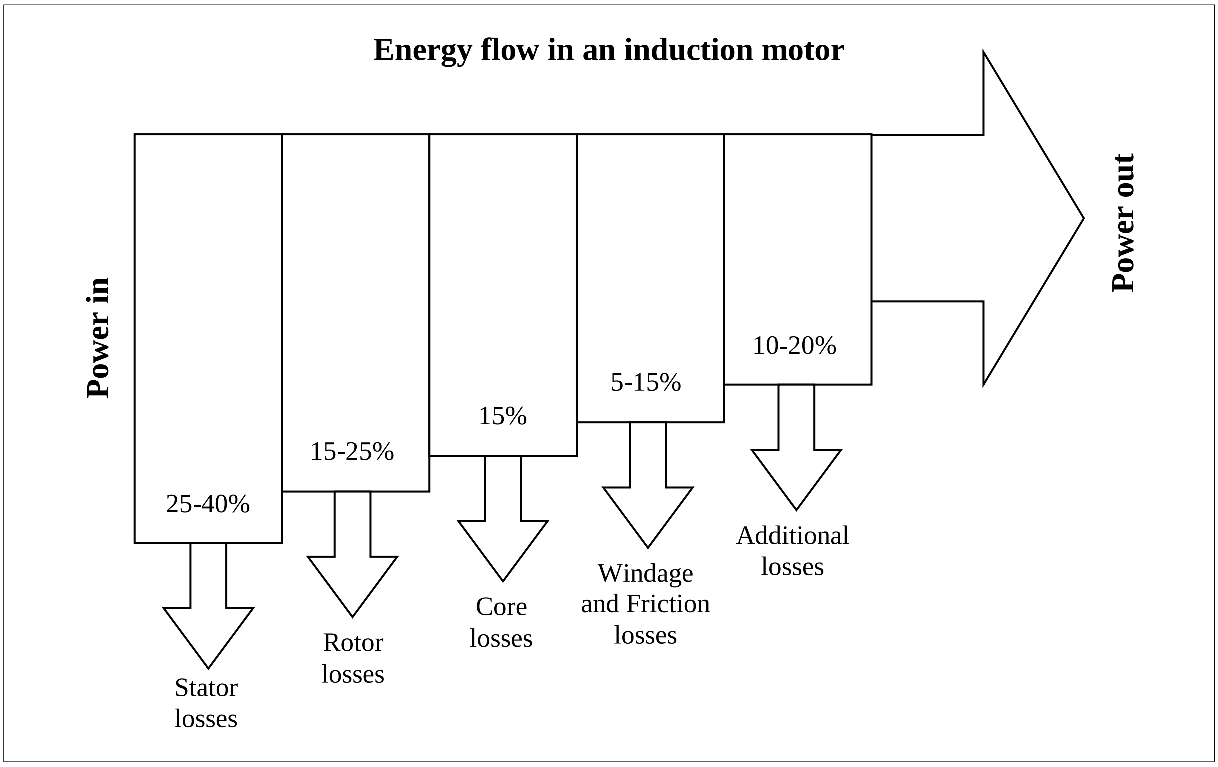


**Figure 16: Typical energy flow in standard induction motors (adapted from [38])**

For each loss in an electric motor, there is a corresponding solution to reducing the specific loss. Although these solutions can only be addressed at the design stage of the motor, they are therefore outside the scope and irrelevant to mention in this study.

## 2.3 Monitoring systems

The term "monitor" is defined as to observe and/or record with instruments that have no effect on the system. Monitoring suggests that a series of observations and/or recordings is made over a period of time. Monitoring is done in order to be able to detect changes within the system over time. Different types of monitoring and monitoring systems exist and is explained in this section of the literature review [35].

### 2.3.1 Types of monitoring

Types of general monitoring are described in Table 1, together with the frequency at which data is monitored, the duration of monitoring and the intensity of the data acquired in the type of monitoring.

**Table 1: Types of monitoring (adapted from** [35]**)**

| General Monitoring Types | | | |
|---|---|---|---|
| Monitoring Type | Measurement Frequency | Monitoring Duration | Data Intensity |
| Trend | Low | Long | Low to moderate |
| Baseline | Low | Short to medium | Low to moderate |
| Implementation | Variable | Duration of project | Low |
| Effectiveness | Medium to high | Short to medium | Medium |
| Project | Medium to high | Project duration | Medium |
| Validation | High | Medium to long | High |
| Compliance | Variable | Dependant on project | Moderate to high |

Depending on the outcome needed for the specific task given, the type of monitoring required for the task can be selected from Table 1. Each type of monitoring requires the frequency at which measurements should be taken. The frequency can vary from several measurements per second to a single measurement per day, depending on the intensity of data required to capture the need for monitoring.

The specific monitoring type required for the project also requires that data be measured for a certain duration. The duration of monitoring can vary from several minutes to years depending on what the outcome of the project should be. The amount of data acquired from each monitoring type will vary depending on the operational characteristics of the project and the required outcome of the project.

This research requires one type of monitoring, trend monitoring. Trend monitoring is used in this research to capture the rate at which the efficiency of the pump decreases after a certain amount of operating hours. The data intensity of this type of monitoring will be low as it is done over a long period of time at a low measurement frequency. Very little data is needed to calculate the efficiency of the pump set.

### 2.3.2 Methods of monitoring systems

Numerous types of monitoring exist which can be used in industrial settings. These types of monitoring range from manual systems, such as recording data in a logbook taken from analogue meters, to advanced technological systems where data is collected via measuring devices. This data is processed by a central processing unit (CPU) and stored electronically. The latter monitoring system is commonly known as an Industrial Control System (ICS).

Although it is called a control system, a major part of the system is dedicated to monitoring. Without monitoring the system one cannot make an informed decision on how to control the process. Typically ICSs are used in industrial settings such as water and wastewater plants, manufacturing plants, oil and gas plants, pharmaceutical plants etc [36].

An ICS comprises of numerous control systems such as Supervisory Control and Data Acquisition (SCADA) systems, Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC). Both SCADA and DCS systems make use of PLCs as components to control a complex industrial system [36].

The most common system used in pump stations of DWS is the SCADA system. The SCADA system is situated at a centralised location to a network of pump stations within a certain area. From this centralised location, numerous pump stations can be controlled and monitored.

The SCADA systems' purpose is to collect data from the hardware at the pump stations, send it to a CPU from where the information is displayed on a monitor to the operator. The hardware situated on site enabling the SCADA system to control and monitor the pump station is the PLCs [36].

A typical pump station monitoring system consists of sensors measuring vibration, pressure, temperature, flow, electrical current, voltage, power and phase angle. All these measurements, taken by the relevant sensors, are sent to the PLC where the measurements are processed. Depending on the set parameters for the specific measurement taken, the PLC sends out the appropriate response to an actuator or any type of hardware that is able to perform a remedial action.

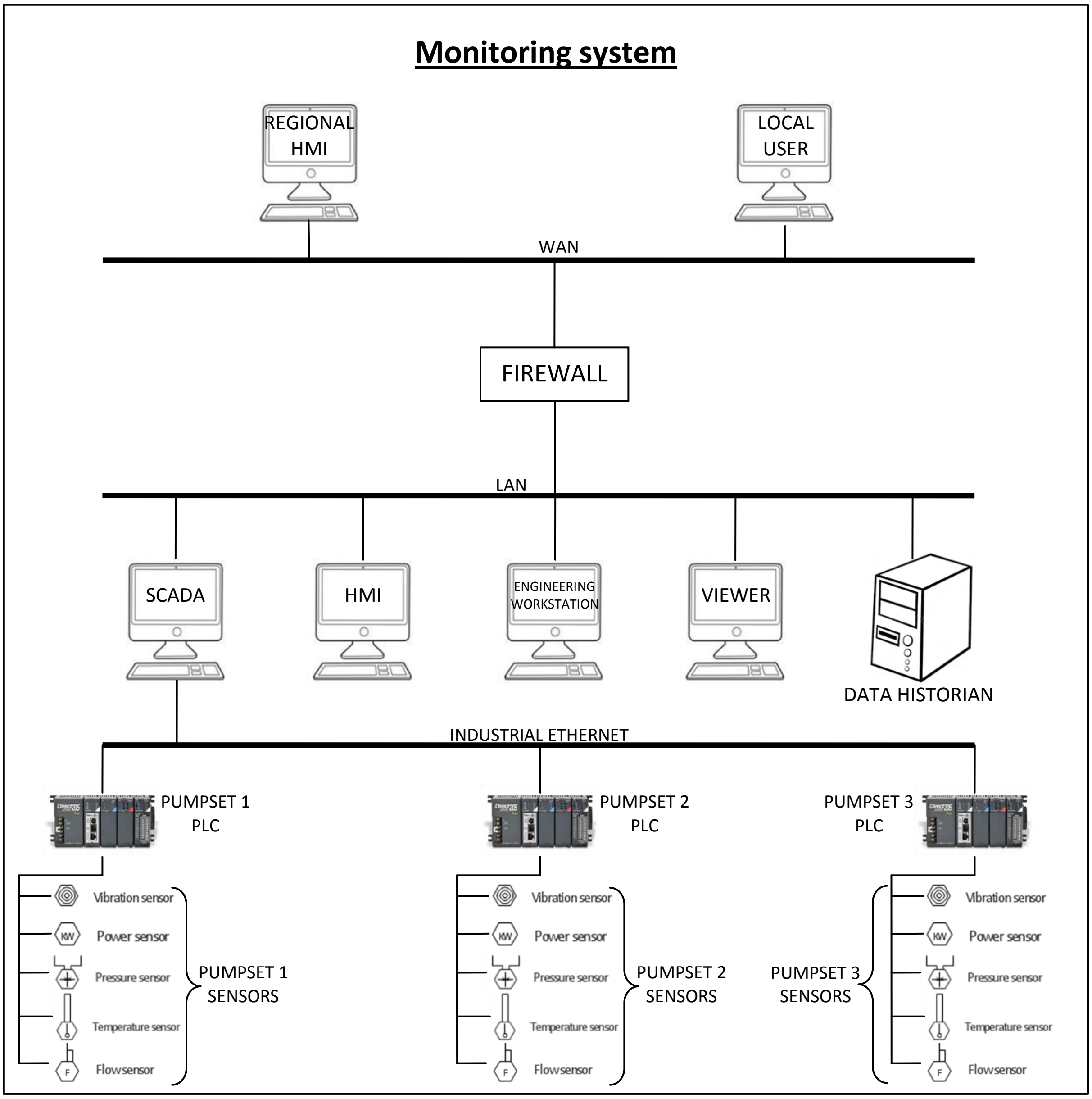


**Figure 17: Industrial digital monitoring system**

Figure 17 shows a typical SCADA monitoring and control system used in DWS pump stations. The first level of the system comprises of the sensors measuring the required information and the PLCs to which this information is sent and processed. Within the pump station, these PLCs are connected via industrial Ethernet.

The second level of the monitoring system is named the primary control centre. The primary control centre comprises of the SCADA system whose functions are as described earlier in this section. Also within the primary control centre are the Human Machine Interface (HMI), engineering work station, a viewer unit and the data historian. All these components are connected via a Local Area Network (LAN). Depending on the location of the primary control centre, the connection between the industrial Ethernet and the SCADA system can either be by LAN or a Wide Area Network (WAN) which is a wireless connection. For redundancy, in case the primary control centre fails, a duplicate backup control centre can be added.

The final level, known as the regional control centre, is connected to the primary control centre via WAN and is located above the primary control centre. The regional control centre provides a higher level of control than allowed by the primary control centre.

The simplest form of monitoring is by physically walking around the equipment and visually inspecting it for any defects such as cracks, leaks and any form of corrosion. Touch is also important for detecting temperature and severe vibration, although caution should be taken not to get burnt when doing the inspection. It is recommended that this type of monitoring should be done by experienced operators and maintenance engineers [22].

### 2.3.3 The importance of monitoring systems

Industrial systems, including pump stations, require some sort of monitoring system. If it is a manual logbook system or high technological system, the monitoring of equipment is essential in keeping the availability and reliability of the equipment up to standard. Monitoring systems in conjunction with proper application of maintenance structures will ensure that the industrial system will operate at maximum efficiency. Also, operating an industrial system at maximum efficiency will result in extending the lifespan of the system to a maximum.

The importance of monitoring systems in pump stations is twofold, to determine the physical condition of the equipment giving the maintenance team an indication whether maintenance is required, and to monitor the energy consumption and effectiveness (performance) of the equipment in the pump station. It is inherent that when the physical condition of the equipment deteriorates, the effectiveness of the equipment will also deteriorate.

Vibration monitoring is said to be the foundation to most maintenance programs. Monitoring vibration enables the operator and maintenance engineer to identify faults at the onset thereof long before failure may occur, ultimately saving money on maintenance costs and preventing any unnecessary decay in the equipment efficiency [37].

Figure 18 shows a comparison between the remaining life of a centrifugal pump for instance, after the onset of a fault compared to the repairing cost. It is clear from the figure that the increase in repairing cost is exponential as the remaining life decreases rapidly after the occurrence of a fault. In most cases when a fault occurs, it is not possible to detect the fault by visual or audible inspection.

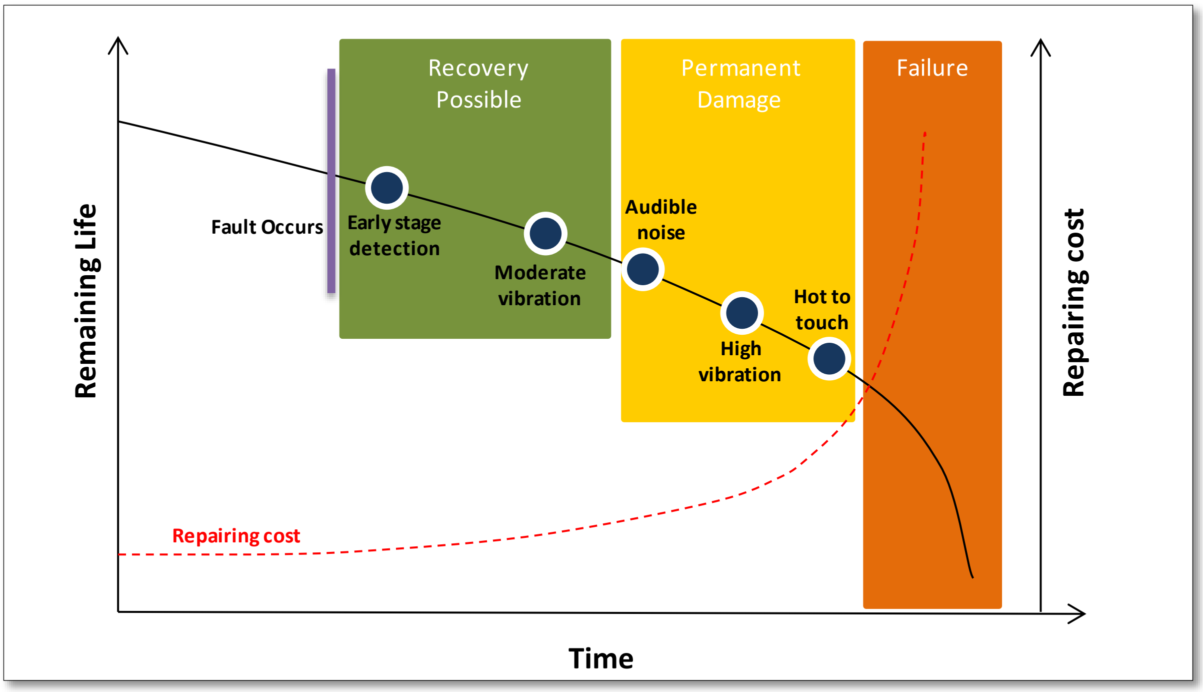


**Figure 18: Pump remaining life vs. cost to repair (adapted from** [22]**)**

Seen in the figure above, when the fault is detectable by human senses such as noise and touch, permanent damage has already been made to the component. In order to detect the fault early enough where recovery is possible, an adequate monitoring system is needed which is capable of notifying the operator or maintenance engineer at the onset of the fault.

It was found by O'Rielly [38], that a strong need exists for companies to measure their energy consumption to enable them to improve their energy efficiency. Without monitoring, it is impossible to determine the cause of an increase in the energy consumption within the plant. Monitoring energy usage of the plant, not as a single lumped value, but monitoring each sub-systems' energy usage will enable the manager to make an informed decision as to where an intervention, or maintenance, is required to increase the performance of the plant [38].

## 2.4 Failure modes and corrective procedures

Failures and faults have a direct negative impact on the efficiency of centrifugal pumps. The failure of centrifugal pump components, or even the components within induction motors, will render the system as unable to perform at its initial designed efficiency. Therefore it is important to know what kind of failures can occur within centrifugal pumps, and induction motors, and what corrective procedures can be performed to reinstate the systems' intended efficiency.

According to Söderholm [39], the literature on failures and faults is not stringent. Söderholm [39] describes a failure as "the termination of the ability of an item to perform a required function". Söderholm[39] also describes a fault as "a state of an item characterized by inability to perform a required function, excluding the inability during preventative maintenance or other planned actions, or due to lack of external resources”. From these two definitions it is derived that a failure is an event, whereas a fault is a state [40].

### 2.4.1 Centrifugal pump failure modes

The first type of failure in centrifugal pumps is hydraulic failures. Hydraulic failures of centrifugal pumps are mainly caused by changes in pressure in the volute of the pump or by the changes in pressure due to the pipes leading to the pump. Table 2 gives a number of hydraulic fault modes that can occur in centrifugal pumps, symptoms of the specific fault mode and corrective procedures to remedy the fault, if any [41].

**Table 2: Hydraulic centrifugal pump failure modes** [41]

| Hydraulic failures | | |
|---|---|---|
| Fault mode | Fault symptoms | Corrective procedure |
| Cavitation | • Erosion<br>• Noise<br>• Vibration<br>• Reduction of pump efficiency | • Increase Net Positive Suction Head NPSH available<br>• Increase or decrease suction pressure<br>• Increase or decrease flow rate to pump designed flow rate<br>• Install correct pump for the operating conditions |
| Pressure pulsations | • Instability of pump controls<br>• Vibration<br>• Pump noise | • Shifting resonant frequencies in piping<br>• Change mode of operation<br>• Install bypass around pump<br>• Replace impeller with one containing more or less vanes<br>• Install acoustical filters |
| Radial thrust | • Packing failures<br>• Mechanical seal failures<br>• Shaft failure<br>• High bearing temperatures<br>• Bearing failure | • Operate pump closer to BEP<br>• Install bypass around pump<br>• Design volute geometry to minimise radial thrust |
| Axial thrust | • Metal fatigue<br>• High bearing temperatures<br>• Bearing failure<br>• Shaft failure | • Make use of a thrust bearing<br>• Operate pump closer to BEP<br>• Install bypass around pump<br>• Substitute shaft material of higher endurance limit |
| Suction and discharge recirculation | • Crackling noise produced at suction or discharge of the pump | • Reduce suction specific speed<br>• Increase output flow<br>• Install bypass around pump<br>• Substitute impeller material more resistant to cavitation<br>• Increase pump output capacity<br>• Modify impeller design |

The second failure types in centrifugal pumps are mechanical failures. Mechanical failures of centrifugal pumps are mainly caused by the physical failure of parts of the centrifugal pump. Table 3 gives a number of mechanical fault modes that can occur in centrifugal pumps, symptoms of the specific fault mode and corrective procedures to remedy the fault, if any.

**Table 3: Mechanical centrifugal pump failure modes** [41][42]

| Mechanical failures | | |
|---|---|---|
| Fault mode | Fault symptoms | Corrective procedure |
| Bearing failure | • Vibration<br>• Increased bearing temperature<br>• Failed bearing | • Check for moisture contamination<br>• Check for any hydraulic faults that may result in overloading of the bearing and follow the suitable corrective procedure<br>• Check bearing oil level<br>• Check for foreign matter in lubrication<br>• Lower bearing speed<br>• Check pump and driver alignment<br>• Check thermal expansion of shaft vs. thermal expansion of bearing<br>• Check manufactured quality of bearing and bearing housing |
| Seal failure | • Wear on shaft<br>• Leaking seal | • Keep stuffing box within specified temperature<br>• Control stuffing box temperature |
| Lubrication failure | • Lubrication viscosity decrease<br>• Formed varnish residue<br>• Solid particles in lubricant | • Control lubrication temperature |
| Excessive vibrations | • Impeller vibration (1x running speed frequency)<br>• Hydraulic vibration (1x running speed frequency)<br>• Baseplate vibration<br>• Bearing housing vibration<br>• Shaft vibration (1x running speed frequency) | • Check for pitted impeller<br>• Increase NPSHA by making use of a bypass<br>• Install levelling screws, grout fill holes<br>• Alter bearing housing mass and/or stiffness |
| Fatigue | • Formed cracks on component surface<br>• Component fractures | • Use fatigue resistant materials<br>• Alter pump design<br>• Surface treating<br>• Use of highly corrosion resistant materials |

The final failure types in centrifugal pumps are named other failure modes and do not fall under either hydraulic or mechanical failures. These other failure modes can be described as erosive and corrosive modes which result in structural failures of the pump. Table 4 gives a number of other fault modes that can occur in centrifugal pumps, symptoms of the specific fault mode and corrective procedures to remedy the fault, if any [41].

**Table 4: Other centrifugal pump failure modes** [41][42]

| Other modes of failure | | |
|---|---|---|
| Fault mode | Fault symptoms | Corrective procedure |
| Erosion | • Adhesive wear:<br>o Surface disruptions<br>o Material grooving<br>o Transferral of material<br>o Galling<br>• Fretting wear:<br>o Red powdery oxide<br>o Coloured spots or blotches<br>o Eroded surface<br>• Abrasive wear:<br>o Abrasion between ring fit areas<br>o Abrasion at impeller keyway faces<br>• Solid particle impingement | • Adhesive wear:<br>o Ensure no unwanted contact between components exist<br>• Fretting wear:<br>o Adopt tighter clearances<br>o Shrink fit components<br>o Coat or lubricate contacting surfaces<br>• Abrasive wear:<br>o Check wear ring clearances according to particles in pumped fluid |
| Corrosion | • General corrosion:<br>o Produced metal oxide<br>• Dealloying:<br>o Formed apertures<br>• Galvanic corrosion:<br>• Stress corrosion cracking<br>• Hydrogen embrittlement:<br>o Cracking<br>o Blistering<br>o Hydriding<br>• Microbiologically induced corrosion:<br>o Saucer-shaped pit containing wet black deposit<br>• Intergranular corrosion: | • General corrosion:<br>o Add protective coating<br>• Dealloying:<br>o Pumped fluid high mineral content<br>• Microbiologically induced corrosion:<br>o Ensure no stagnant water occur |
| Excessive power consumption | • Gradual increase in power consumption over time<br>• Motor trip on over load | • Periodic tracking of control valve position<br>• Recording of motor current and voltage<br>• Measure pump shut-off head<br>• Replace leaking gaskets<br>• Repair leaks<br>• Reduce impeller speed<br>• Restore clearances<br>• Reprime pump |
| Blockages | • Decreased flow rate | • Remove objects causing blockages |

### 2.4.2 Induction motor failure modes

Induction motors are very rugged machines due to their simple construction and contain few components that are able to fail. Three types of failure modes of induction motors are discussed in this section. A study of 6000 utility industry motors that were undertaken in 1985 found that 53% of electrical motors fail due to mechanical failures [34]. The failures were allocated as shown in Figure 19.

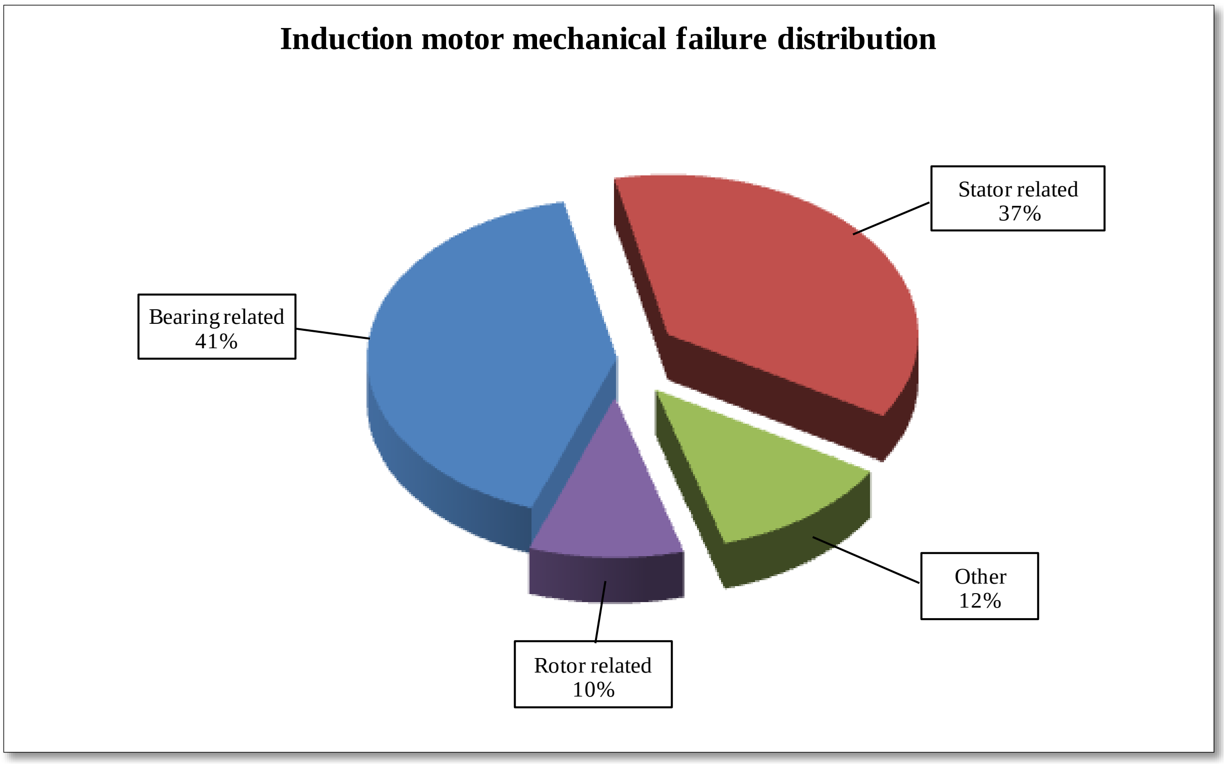


**Figure 19: Distribution of electrical motor failures** [34]

As seen in Figure 19, the leading cause of mechanical failures in induction motors are due to bearing failures. The main causes of bearing failures are listed hereunder [34]:

- Contamination - 45% to 55%
- Lubrication - 11% to 17%
- Improper assembly - 11% to 13%
- Misalignment - 10% to 13%
- Overloading - 8% to 10%
- Other - 1% to 6%

The second type of failure found in induction motors are due to electrical failures. Electrical failures are most commonly caused by high temperature or overloading of the electrical motor. Electrical failure are also caused by other factors such as:

- Variation in supply voltage;
- Poor electrical connections;
- Vibration;
- Contamination in the insulation and;
- Single phasing.

The third and final type of induction motor failure is due to misapplication. Misapplication can be caused by specifying the wrong motor for a specific duty, such as where the driven load torque requirements are greater than the torque produced by the motor. Misapplication is also caused when a specific motor is moved from its service for which it is designed to another service of which the load requirements are not known [34].

## 2.5 Maintenance techniques

Maintenance is crucial to keeping machinery in good working order. Without maintenance the reliability of the system will be very poor, breakdowns will occur frequently causing production loss and the efficiency of the plant will be relatively low. The low efficiency will result in unnecessary additional electrical costs than is needed to perform the specific task, eventually leading to a loss in profit. This section will focus on what types of maintenance structures exist and how they are implemented to ensure a high reliability of equipment and improved efficiency. Figure 20 shows the different types of maintenance and how they are implemented.

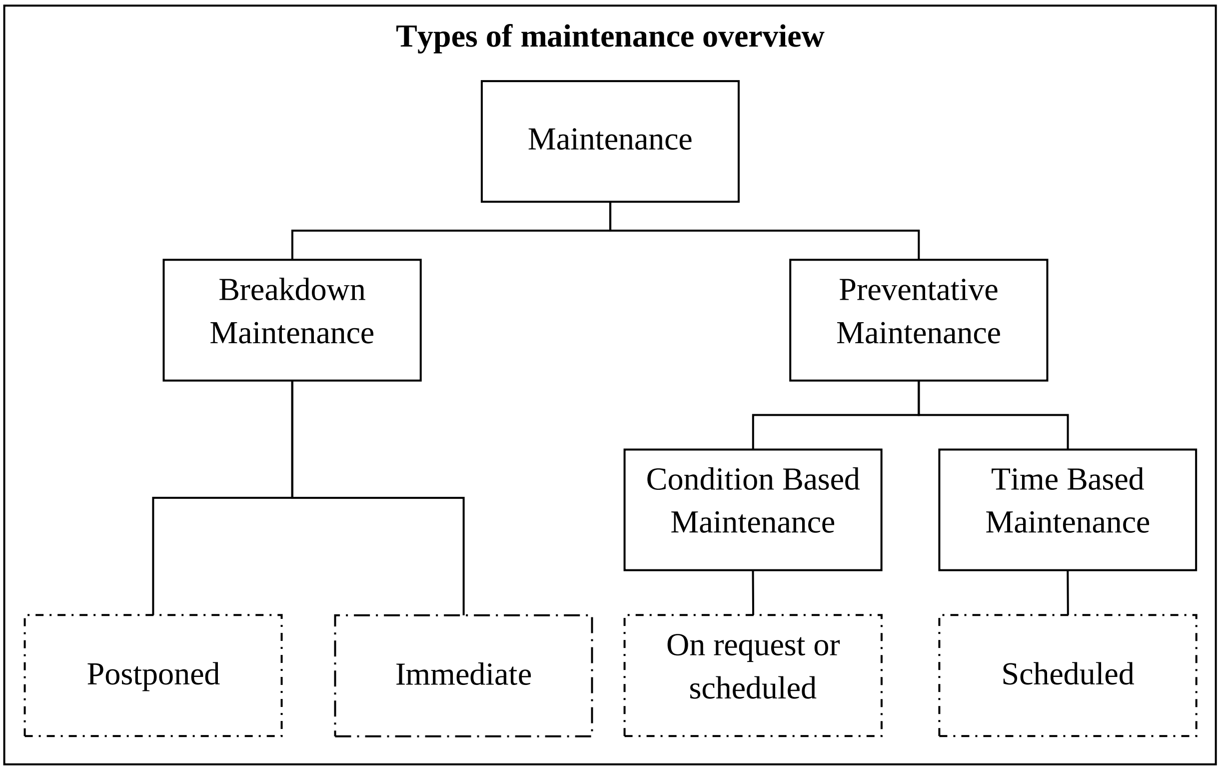


**Figure 20: Maintenance types overview (adapted from** [40]**)**

As Beebe [43] stated, the underlying purpose of maintenance is to ensure that a plant is capable of providing the required production capacity at the lowest cost possible. In the case of bulk water pump stations, production is specified as the ability to deliver the required amount of water within the specified time frame. Beebe [43] also stated that maintenance should be regarded as a reliability function and not as a repair function.

Basically, only two types of maintenance exist: 1) Breakdown maintenance and, 2) Preventative maintenance [40][43]. These will be discussed in the following two sections.

### 2.5.1 Breakdown maintenance

Breakdown maintenance can be a cost-effective solution, given that the cost of repairing the pump is justified. In this case repairs are done only when necessary which might lead to spending a minimum on maintenance costs, but this will not always be the case. Breakdown maintenance is also known as run-to-failure, which can mean that the pump may continue to operate but it fails to produce the expected outcome. The failure can be seen as an "economical failure" where the input operational costs remain the same but the production delivery decreases. This ultimately leads to a decrease in system efficiency.

### 2.5.2 Time based maintenance

Bengtsson [40] described preventative maintenance as "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item". Preventative maintenance is mainly divided into two types of maintenance: 1) TBM, and 2) CBM.

TBM is a conventional type of maintenance where maintenance procedures are based on a fixed time schedule. It is assumed that the failure behaviour of machines can be predicted, and based on this prediction, maintenance schedules are made. The maintenance schedule of these machines can be after a certain amount of operating hours or the decisions can be made based on fixed intervals such as weekly, monthly or yearly. An example of TBM checks on a centrifugal pump is given in Table 5.

**Table 5: Pump maintenance checklist and recommended intervals (adapted from** [44] **and** [45]**)**

| Routine check | Daily | Monthly | Biannually | Annually |
|---|---|---|---|---|
| • Check for noisy bearings | √ | | | |
| • Check for cavitation | √ | | | |
| • Check oil level | √ | | | |
| • Check for water in the oil and discoloration | √ | | | |
| • Feel pump bearings for temperature | √ | | | |
| • Feel pump casing for temperature | √ | | | |
| • Check for oil leaks | √ | | | |
| • Check if gland packing seal leaks are normal | √ | | | |
| • Check mechanical seal for leaks | √ | | | |
| • Check pump casing for leaks | √ | | | |
| • Add oil to bearings if required | | √ | | |
| • Clean oil level indicators and oil bulb as required | | √ | | |
| • Clean out bearing brackets and open drain hole | | √ | | |
| • In case of pump in standby and not running: Overfill bearing housing and rotate pump by hand to coat the bearing with oil | | | √ | |
| • Inspect coupling for cracks and wear, tighten bolts | | | | √ |
| • Check coupling alignment | | | | √ |
| • Check axial float of the pump and driver shaft | | | | √ |
| | | | | |
| In case a pump is opened for part replacement, this instance should be treated as an opportunity to inspect and, if necessary, replace the following parts: | | | | |
| • Inspect bearing housing for cracks and wear | | | | √ |
| • Inspect the shaft and sleeve for wear and grooves | | | | √ |
| • Inspect the casing for pitting and wear | | | | √ |
| • Check wear ring clearances | | | | √ |
| • Inspect the impeller for wear, corrosion and cavitation | | | | √ |
| • Inspect gaskets | | | | √ |
| • Inspect seal chamber for wear, corrosion and pits | | | | √ |

In order to make good use of TBM, extensive failure time data for the specific machine is required to make an informed decision. These data sets or failure rate trends are called bathtub curves. An example of a bathtub curve is shown in Figure 21. These bathtub curves have three phases namely: burn-in life time, useful life time, and wear-out life time [19].

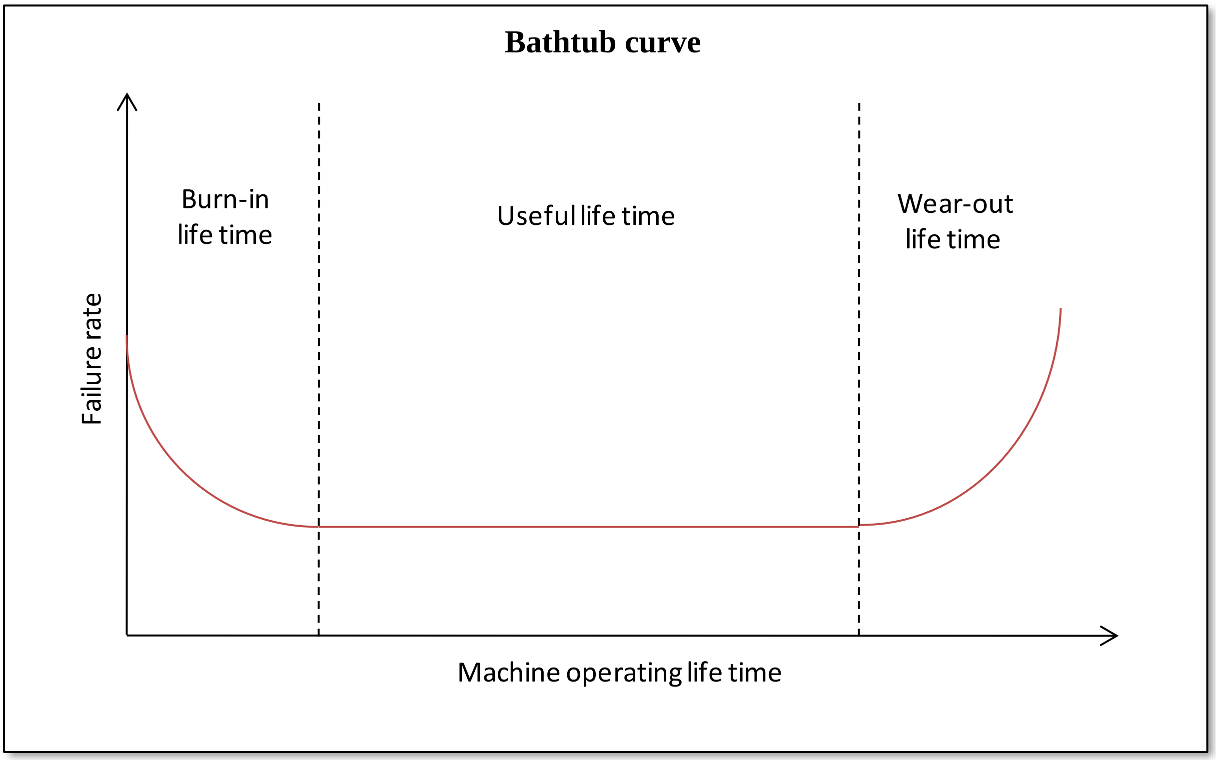


**Figure 21: Bathtub curve (adapted from** [19]**)**

The bathtub failure rate curve is not the only form that these curves adopt. The bathtub curve is one of six forms that these reliability curves can adopt. These failure rate curves were developed by United Airlines. Due to the focus of this dissertation, further information about these curves can be found in the following articles [40][46].

### 2.5.3 Condition based maintenance

The second type of preventative maintenance is called CBM. This type of maintenance does not solely focus on detecting faults and diagnostics of equipment but it is also used to detect degradation of equipment and is able to predict failure to some extent.

CBM relies on decision making through constantly monitoring the condition of equipment. CBM has advantages and disadvantages. Although there are very few disadvantages, the most prominent disadvantage is that the cost of investing in CBM is usually very high. Implementing CBM in already existing infrastructure requires extensive remodelling of monitoring hardware and requires training of staff [47].

Despite the disadvantages of CBM, it is to date the most popular and modern technique for monitoring equipment [19].

Condition monitoring can be done by several techniques as listed hereunder. These techniques require monitoring of the following equipment conditions:

- Vibration;
- Sound and acoustic;
- Oil-analysis or lubricant;
- Electrical and;
- Temperature.

Another condition monitoring technique that should be taken more seriously is performance monitoring [19].

According to Ahmad [19], CBM can be divided into two stages: diagnosis and prognosis. Diagnosis is defined as the process of finding the source of a fault and provide early warnings to the maintenance engineer whilst the equipment is still operating in a deteriorating state. Prognosis is defined as the process of predicting when the failure may occur and as such, still be able to utilise the equipment until just before a failure occurs [19].

Figure 22 gives a graphical presentation of what CBM achieves considering the performance cost and maintenance cost of equipment such as pumps. From Figure 22 it is evident that TBM results in high maintenance costs and low performance costs. Performance cost can be defined as the cost incurred due to a loss in efficiency in the system. High maintenance costs in TBM are due to frequently carrying out maintenance on a predetermined schedule which results in unnecessary maintenance being done before its time. A lower system efficiency results in an increase in operational costs to continue to deliver the same amount of product.

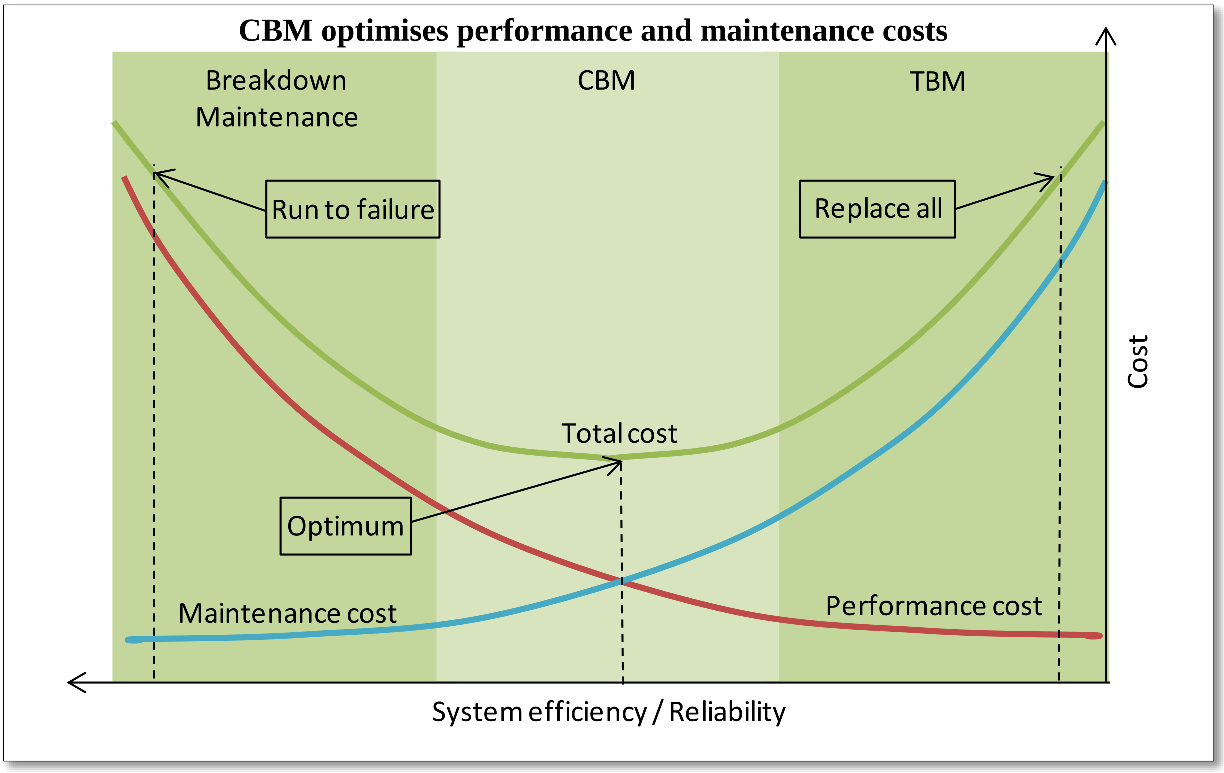


**Figure 22: CBM optimises performance and maintenance cost (adapted from** [48]**)**

Breakdown maintenance may result in the same total costs as TBM, however, the greater portion of the costs of the total cost are due to performance cost. Maintenance costs in breakdown maintenance are kept to a bare minimum, while, due to the equipment operating at a very low efficiency, the performance cost is very high in this maintenance structure. Finally, CBM tends to seek the minimum total cost, considering the performance cost and maintenance cost, to operate the equipment. This is done by seeking the optimum time when to do maintenance so that the total costs are kept at a minimum. CBM comprises of three main steps [49]. These steps are shown in Figure 23 below.

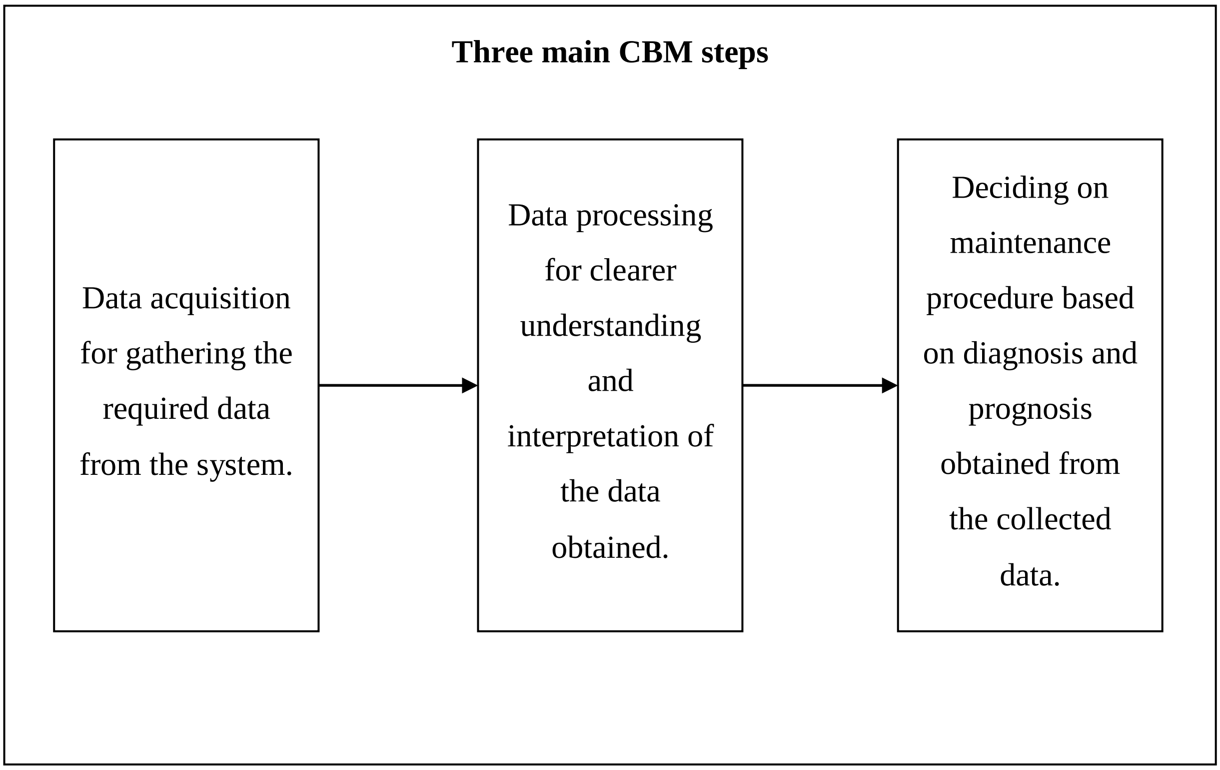


**Figure 23: Three main CBM steps**

The basis on which CBM functions is by using diagnostic tools for "continuously" monitoring the degrading symptoms of equipment, and with prognosis based on the evolution of the physical characteristics and performance of equipment that lead to failure, to make an informed decision on a maintenance procedure to follow. Following this CBM strategy, downtime of the system will be minimised by balancing the risk of failure and performance costs [50].

According to Lee [50], a substantial amount of diagnostic tools, together with diagnostic methods, have been developed with great success. However, the development of sound prognostic methods have not been developed yet as the current methods remain focused on traditional signal processing methods [50].

Finally, CBM seems to be the more realistic maintenance approach when comparing it to TBM and breakdown maintenance. As Ahmad [19] stated, 99% of equipment failures are preceded by certain indications that are detected via diagnostics. Following the TBM structure, these indications will not be detected in time and unnecessary high maintenance costs will be the result thereof. CBM follows the optimisation approach as shown in Figure

22, eliminating the unnecessary high maintenance costs and unnecessary loss due to high performance costs [19].

Wang [51], has developed a Non-Homogeneous Poisson Process model which was used for modelling failure events. A cost benefit analysis was implemented after the development of the Non-Homogeneous Poisson Process. By considering the condition monitoring system, a breakeven point was found between the required condition monitoring system and expected lifecycle benefits. Wang also, with the aid of the cost benefit analysis, determined optimal maintenance strategies in order to minimise operation and maintenance costs.

## 2.6 The benefits of maintaining a high pump system efficiency and load shifting

The previous sections in Chapter 2 discussed the following:

- What events lead to a reduction in a pump system efficiency,
- How the performance of a pump system can be monitored,
- What remedial actions can be taken against faults causing a reduction in pump system performance and,
- How these remedial actions can be handled with different types of maintenance structures.

This section of Chapter 2 will focus more on existing literature which has been found when all of the mentioned criteria have been implemented and what possible savings were realised in the respective cases.

From a paper presented by Maddy at the 68th Annual Water Industry Engineers and Operators Conference in Melbourne [52], it was found that after testing 23 pumps from four different pump stations, an overall efficiency increase of 2% - 4% at these pump stations could realise AU$109,000 to AU$ 218,000. The increase in efficiency of the pumps will be done through overhauling pumps and through revised pumping regimes [52].

A case study by the U.S Department of Energy [53], proved that by correct implementation of pumps, the energy consumption of a sewerage plant was reduced by 15%. These energy savings resulted in an annual savings of US$2,960 which realised a payback time of 5.4 years once implemented. These savings were made possible by installing a small booster pump to empty a reservoir at a reduced rate than what the original installed pumps would do. This smaller pump operates at extended times, however, the total friction losses within the system are less due to the reduced flow rate. This ultimately led to the mentioned energy savings [53].

An article by Antonios [54], does not present the effects of maintaining a high pump system efficiency, but it describes three different methods on how to predict the efficiency of a centrifugal pump. The first method that Antonios describes is the exact solution of the Navier-Stokes equations. The second method he describes is based on empirical laws from laboratory measurements. His final method of predicting centrifugal pump efficiency is a new empirical law which takes into account geometrical and operating centrifugal pump parameters. Through testing six different centrifugal pump impellers, with varying specific speeds from 15 to 85, Antonios found that the numerical predictions and experimental data agreed satisfactorily across a wide range of flow rates [54].

A global report published by the Water Research Foundation [55], compiled a compendium of case studies on practices for energy efficient design of water industry assets. The foundation found that larger savings can be realised by adopting improved maintenance structures as well as operating pumps closer to their duty points. From the factsheets in the report, the following table summarises the potential energy savings from the case studies in the research specifically to centrifugal pumps [55].

**Table 6: Pump efficiency interventions and potential savings** [55]

| Factsheet | Potential interventions | Range of potential savings |
|---|---|---|
| Duty point selection | Select pump with BEP closer to the normal duty | Up to 11% |
| Duty range selection | Select multiple pumps for a wide duty range | Up to 3% |
| Change of duty | Check pump selection when duties change | 5% to 20% for single pumps |
| Variable duty selection | Use VSDs for a wide duty range | Up to 12% |
| Variable speed drives | Correctly size pumps<br>Utilise VSDs for varying duties | Up to 37% |
| Pipework system design | Check hydraulic restrictions against duty | 5% to 20% for single pumps |
| Waste water pumping | Check hydraulic restrictions against duty | Up to 5% |

| | | |
|---|---|---|
| Intrinsic efficiency | Check with pump maker or maintenance | Up to 19% |

It is clear from Table 6 that with the correct implementation of the correct intervention, potential savings of 3% - 37% can be realised.

A wastewater treatment plant in Ontario, California implemented a project where eddy current clutches were removed from pumps as the need to operate the pumps at different speeds were not necessary anymore and the maintenance costs on the eddy current clutched were very high. Together with this clutch removal implementation, most of the electrical motors were replaced with high efficiency motors. The new motors were 4% - 6% more efficient than the existing motors. The results of this project led to maintenance costs being reduced by US$14,000 per annum, and the cost saving due to the removal of the eddy current clutches led to the plant's annual energy consumption being reduced by 10% [56].

Van Greunen [57] did a study on improving the energy efficiency of cooling plants in gold mines of South Africa. He focused on saving energy by installing VSD on the evaporator and condenser pumps of the chillers. By making use of a real-time energy management program to control the VSDs and monitor the systems, van Greunen was able to realise an estimated energy saving of 13.6% (600kWh daily savings) on the evaporator and condenser pumps alone. This energy savings meant a savings of R2,275,000 per annum based on the 2012/2013 Eskom Megaflex tariff structure [57].

Nortjé [58] identified a number of national pump stations in the Usutu-Vaal water distribution scheme as prime candidates for DSM interventions. These pump station are named Grootdraai, Tutuka, Grootfontein and Rietfontein. Nortjé made use of Real-time Energy Management System software program to control and optimise the system by shifting a combined load of 12.6 MW away from the hours of 18h00 to 20h00. By shifting the load to cheaper energy time frames of the day, Nortjé was able to realise an annual savings of R4,765,000 [58].

Els [59] found it plausible to implement load management on water treatment plants (WTP). Shown in Figure 24, also referenced by Els, the main energy consumer in WTPs are high service pumping. By making use of an Energy Management Systems (EMS), Els was able to shift load of the WTP out of the peak energy times of use (TOU) times. Els also developed a control philosophy for controlling the WTP and with the combination of the EMS and control philosophy, an average peak load shift of 2.21 MW was realised. This load shift meant that an annual cost saving of R1,000,000 could be realised [59].

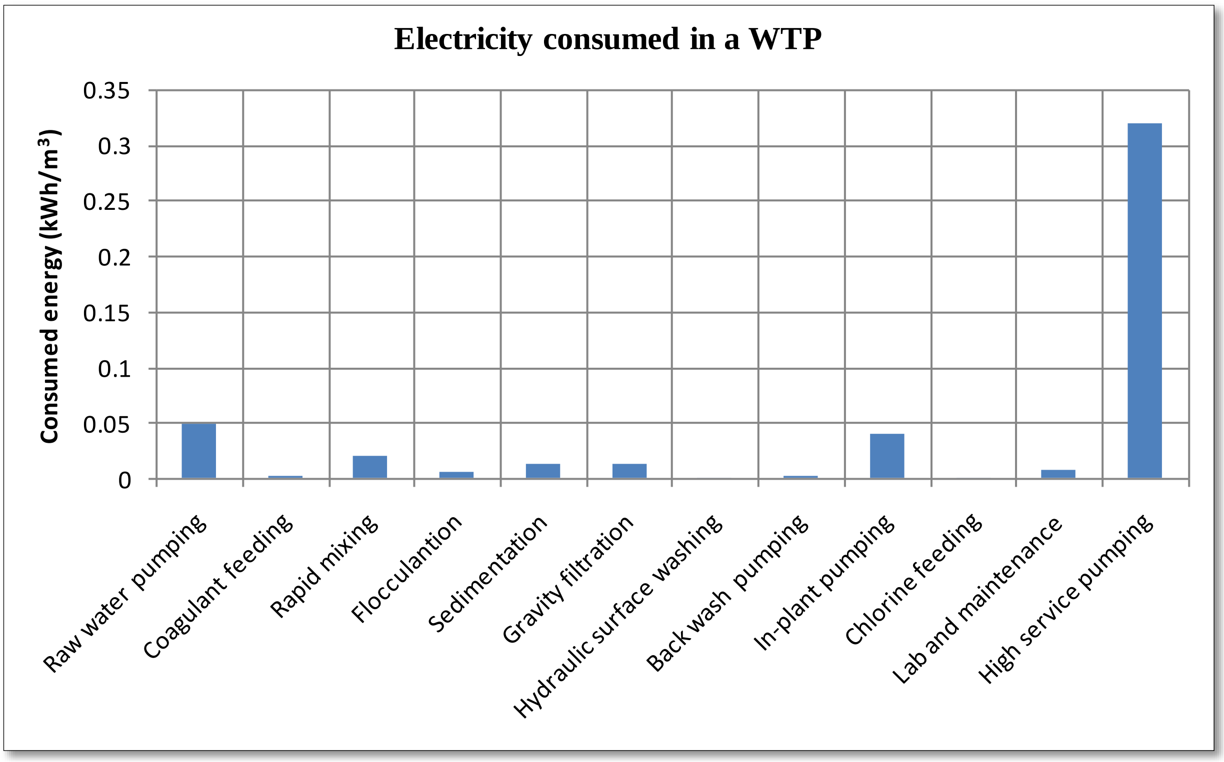


**Figure 24: Electricity consumed in a WTP (adapted from** [60]**)**

Grobbelaar [61] created a maintenance procedure on pumping projects that improved the sustainability of dewatering systems in mining, although, his maintenance procedure can be implemented on any pumping system. The maintenance procedure consists of four sections which include data loss, mechanical, control and instrumentation, and control parameters. By implementing the maintenance procedure on three gold mines in South Africa, Grobbelaar was able to shift 10.16 MW of load and realise a total savings of R8,050,000 [61].

Beebe [43] reported that efficiency deterioration tests were conducted on over 300 medium to large size split casing pumps. These pumps were from the water industry. It was found that the average efficiency deterioration of these pumps were 8% over a period of 10 years (0.8% per annum). The deterioration of the pumps remained moderately constant between the ages of 12 and 24 years at around 9%, after which it decreased to 16% at the age of 40 years [43].

A study on improving the energy efficiency of pumps was conducted by a contractor ETSU [62]. It was said to be known that a small clean water pump's efficiency could decrease with 20% after operating only two years after commissioning (10% per annum). Also, larger clean water pumps have been reported to lose on average about 5% of their initial efficiency in the first five years of operation (1% per annum). Cast iron casing pumps working with clean water tend to undergo build-up of corrosion products which cause the loss in efficiency [62].

## 2.7 Conclusion

In this chapter the basic principles of centrifugal pumps was discussed. Two types of factors that influence the efficiency of a centrifugal pump, operational factors and mechanical factors, were identified and studied in depth. In conjunction with centrifugal pumps, the same was done with electrical induction motors.

Monitoring of industrial equipment, such as pumps and electrical motors, are of paramount importance. The types of monitoring that exists were introduced and explained. Types of monitoring systems for industrial equipment and the basic subsections of the monitoring systems were discussed. Monitoring is very important to be able to track the condition of the equipment therefore the importance of monitoring was covered.

Monitoring of equipment is ineffective unless the correct maintenance procedures are performed after failure is detected by the monitoring system. Failure of centrifugal pumps and induction motors can occur in many different forms. These forms of failure were discussed in depth.

Finally, literature was found on what the outcomes and saving could be once the correct monitoring and maintenance procedures are followed and implemented on centrifugal pumps and induction motors. Savings on energy costs are possible if the literature in this chapter is followed.

Considering the literature review, no document or article could be found where the effect of efficiency decay on centrifugal pumps was quantified.

# CHAPTER 3

## Energy consumption analysis of pump stations

*Chapter 3*

*In Chapter 3 the method of obtaining data is given. The calculation of the efficiency of each pump set is described, as well as how the efficiency decay is predicted. The method used to calculate the energy cost for a pump set is described.*

# 3 ENERGY CONSUMPTION ANALYSIS OF PUMP STATIONS

## 3.1 Introduction

In this chapter the methodology for the research done is discussed. The method is divided into four stages. The four stages are discussed below.

Stage 1: *Acquire data*

In this stage all the necessary data is obtained from various pump stations. The data is obtained from manually entered logbooks. Due to the nature of the research done it is impossible to generate new data within the available time frame. Ample time is needed for a pump's efficiency to deteriorate and due to time constraints, and for this research, existing data is used.

Stage 2: *Calculating the efficiency*

The ultimate goal is to calculate the efficiency decay of the pump over time and the possible energy savings if correct maintenance were to be implemented on the pumps. The efficiency of each pump set is calculated using the conventional method. Certain constraints exist such as knowing the flow rate through the specific pump. In some cases, only one flow meter could be installed at a pump station measuring the total flow rate from the pump station. A method is formulated to calculate the flow rate of the specific pump through Gauss elimination.

Stage 3: *Predicting efficiency decay*

After knowing the efficiency of a pump, the efficiency decay is predicted by making use of linear regression. The formulas for predicting the efficiency decay through linear regression are given. Guidelines for interpreting the result of a predicted efficiency decay is tabulated.

Stage 4: *Determining the energy consumption*

In this stage the Cumulative Additional Cost (CAC) due to the decay of a pump's efficiency is formulated and calculated over a period of five years of continuous operation. The charges included in the calculation are tabulated and the formula for calculating the operational cost is formulated. The Pump Energy Indicator (PEI) is introduced which is used to determine the maintenance interval for a simulated maintained pump. The Maintained Cumulative Additional Cost (MCAC) is calculated.

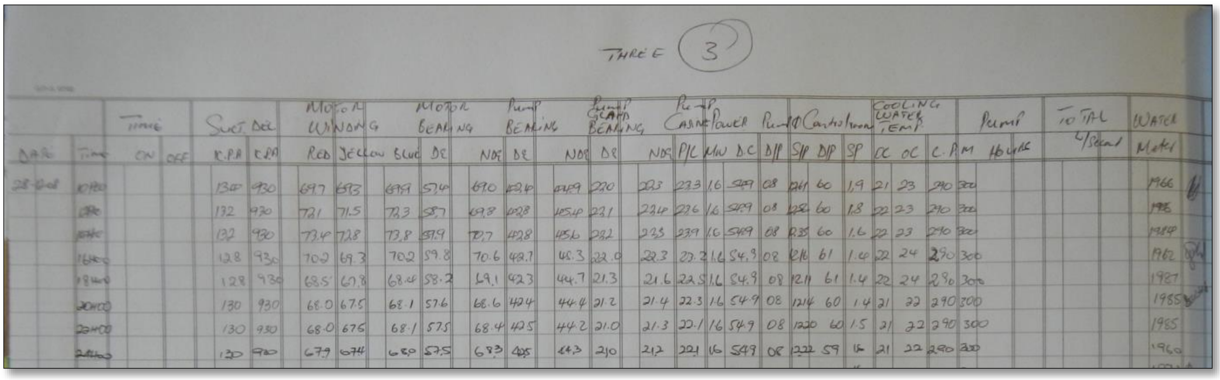
## 3.2 Data acquisition

In this section the acquisition of data from pump stations necessary to calculate the performance of a pump, more specifically the efficiency of the pump, is discussed. Data was acquired from a number of DWS pump stations. The data that was acquired was in the form of hand written logbooks.

### Pump station data

As previously mentioned, data was acquired from various DWS pump stations in the form of logbooks. Data over a long time span is required in order to be able to predict the decay of a pump's efficiency. A pump operating a few days does not have a noticeable effect on the decay of a pump's efficiency. Photos were taken of the logbooks of each individual pump station in increments of a month. An example of recorded data is shown in Figure 25. The longest possible time span that could be acquired from the logbooks was recorded. The pump stations of which data was acquired are listed below:

1. Grootdraai pump station
2. Tutuka pump station
3. Grootfontein pump station
4. Rietfontein pump station
5. Heyshope pump station



THREE ③

| | | TIME | | SUCT. | DEL | MOTOR WINDING | | MOTOR BEARING | | PUMP BEARING | | PUMP GLAND BEARING | | PUMP CASING | POWER | | PUMP | | Cavitation | | | COOLING WATER TEMP | | | PUMP | | TOTAL | WATER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DATE | TIME | ON | OFF | K.P.A | K.P.A | RED | YELLOW | BLUE | DE | NDE | DE | NDE | DE | NDE | P/C | MW | D.C | D/P | S/P | D/P | SP | CC | OC | C.P | M | HOURS | L/Second | Meter |
| 28-[illegible] | 10H00 | | | 130 | 930 | 69.7 | 69.3 | 69.9 | 57.4 | 69.0 | 43.4 | 44.9 | 22.0 | 22.3 | 23.3 | 1.6 | 54.9 | 08 | 1261 | 60 | 1.9 | 21 | 23 | 290 | 300 | | | 1966 |
| | 12H00 | | | 132 | 930 | 72.1 | 71.5 | 72.3 | 58.7 | 69.8 | 42.8 | 45.4 | 23.1 | 22.4 | 23.6 | 1.6 | 54.9 | 08 | 1252 | 60 | 1.8 | 22 | 23 | 290 | 300 | | | 1985 |
| | 14H00 | | | 132 | 930 | 73.4 | 72.8 | 73.8 | 59.9 | 70.7 | 42.8 | 45.6 | 23.2 | 22.5 | 23.9 | 1.6 | 54.9 | 08 | 1235 | 60 | 1.6 | 22 | 23 | 290 | 300 | | | 1984 |
| | 16H00 | | | 128 | 930 | 70.2 | 69.3 | 70.2 | 59.8 | 70.6 | 42.7 | 45.3 | 22.0 | 22.3 | 23.2 | 1.6 | 54.9 | 08 | 1216 | 61 | 1.4 | 22 | 24 | 290 | 300 | | | 1962 |
| | 18H00 | | | 128 | 930 | 68.5 | 67.8 | 68.4 | 58.2 | 69.1 | 42.3 | 44.7 | 21.3 | 21.6 | 22.5 | 1.6 | 54.9 | 08 | 1211 | 61 | 1.4 | 22 | 24 | 290 | 300 | | | 1987 |
| | 20H00 | | | 130 | 930 | 68.0 | 67.5 | 68.1 | 57.6 | 68.6 | 42.4 | 44.4 | 21.2 | 21.4 | 22.3 | 1.6 | 54.9 | 08 | 1214 | 60 | 1.4 | 21 | 22 | 290 | 300 | | | 1985 |
| | 22H00 | | | 130 | 930 | 68.0 | 67.6 | 68.1 | 57.5 | 68.4 | 42.5 | 44.2 | 21.0 | 21.3 | 22.1 | 1.6 | 54.9 | 08 | 1220 | 60 | 1.5 | 21 | 22 | 290 | 300 | | | 1985 |
| | 24H00 | | | 130 | 930 | 67.9 | 67.4 | 68.0 | 57.5 | 68.3 | 42.5 | 44.3 | 21.0 | 21.2 | 22.1 | 1.6 | 54.9 | 08 | 1222 | 59 | 1.5 | 21 | 22 | 290 | 300 | | | 1960 |

**Figure 25: Example of data recorded from Grootfontein pump 3**

Other pump stations were also visited in order to acquire data without any success. Logbooks for these pump stations were available at the time, but the data within these logbooks were insufficient for the purpose of this study. The most common problem noted with these logbooks was that either the flow or the power, or both, was not recorded due to a malfunctioning sensor. The pump stations visited from which no data could be collected are listed below.

1. Geelhoutboom pump station
2. Morgenstond pump station
3. Camden pump station
4. Killburn pump station
5. Driel 1 pump station
6. Driel 2 pump station

Specific data is required to calculate the efficiency of a pump. The data that is acquired from the logbooks are listed hereunder.

- Date
- Suction pressure
- Intermediate pressure (in the case of a booster pump and a main pump)
- Delivery pressure
- Flow rate
- Flow totalized
- Power
- Running hours totalized

The measurement frequency of the data collected is two hourly, which is taken from logbooks kept at the individual pump stations. These logbooks are manually completed by the operator on duty at the time while the pumps are running.

## 3.3 Calculating pump efficiency

In this section all the necessary equations are given and explained that are needed to do the processing of the data concerning the calculation of pump efficiency and predicting the efficiency decay. The ultimate goal of this section is to calculate the pump efficiency decay over time making use of data that was acquired and discussed in Section 3.2. The prediction of the efficiency decay is done by making use of regression formulas. The use of linear and exponential regression is made.

### 3.3.1 Calculating pump efficiency

Using the data that was acquired in Section 3.2, the following procedure was followed to calculate the instantaneous efficiency of the pump. Firstly, the hydraulic power added to the fluid by the pump is calculated using Equation 1.

**Equation 1**

$$P_h = \rho g Q H \text{ [63]}$$

With:

$P_h$ - hydraulic power (power delivered to the fluid)

$\rho$ - fluid density

g - gravitational acceleration 9.81 m/$s^2$

Q - flow rate of the specific pump

H - total head developed in metres

The head change within the fluid, H, from the suction side of the pump to the delivery side of the pump is calculated using Equation 2. Since the suction and delivery pressures are recorded, it is not necessary to do the calculation.

**Equation 2**

$$H = \frac{\Delta P}{\rho g} \text{ [63]}$$

With:

H - total head developed in metres

$\Delta P$ - differential pressure over the pump

$\rho$ - fluid density

g - gravitational acceleration 9.81 m/$s^2$

By substituting Equation 2 into Equation 1 and simplifying it, Equation 3 is obtained which is used to calculate the hydraulic power added to the fluid by the pump.

**Equation 3**

$$P_h = Q\Delta P$$

With:

$P_h$ - hydraulic power (power delivered to the fluid)

$Q$ - flow rate of the specific pump

$\Delta P$ - differential pressure over the pump

After calculating the hydraulic power delivered to the fluid by the pump, the efficiency of the pump is calculated using Equation 4.

**Equation 4**

$$\eta_p = \frac{P_h}{P_t \eta_m}$$

With:

$\eta_p$ - pump efficiency

$P_h$ - hydraulic power (power delivered to the fluid)

$P_t$ - total power input to the motor

$\eta_m$ - motor efficiency

The power readings obtained from the recorded data is the total power ($P_t$) that is supplied to the motor. In order to calculate the efficiency of the pump specifically, the efficiency of the motor is required. For the purpose of this study the efficiency of the motor is not obtained or calculated. For this reason, the efficiency of the specific pump cannot be calculated. Instead the efficiency of the pump set is calculated. Thus Equation 4 is rewritten to form Equation 5. This pump set efficiency is used to predict the efficiency decay.

**Equation 5**

$$\eta_s = \frac{P_h}{P_t}$$

With:

$\eta_s$ - pump set efficiency

$P_h$ - hydraulic power (power delivered to the fluid)

$P_t$ - total power input to the motor

### 3.3.2 Calculating the flow rate for each individual pump set

The most commonly used flow meters within DWS pump stations are ultrasonic flow meters. At numerous DWS pump stations only one flow meter is installed per pump station. These flow meters are installed just outside the pump station in a separate chamber measuring the combined flow rate of the operating pumps. In order to calculate the efficiency of a specific pump set, the flow rate of this single pump set is needed. As shown in APPENDIX B, a method is formulated that will assist in calculating the flow rate of each individual pump set.

The principle on which this method is formulated is through the conservation of energy. The law of conservation of energy states that energy cannot be created nor can it be destroyed. Energy can only be transformed into different forms of energy, being sound, heat, momentum etc. The energy in the system presented by the pump stations are pressure energy and kinetic energy.

The Bernoulli Equation is used as the energy equation from which the final equation for calculating the flow rate through each individual pump line is derived. To successfully make use of this method, a set of individual equations equal to the number of pump lines within the pump station needs to be derived. The number of unknown variables in these equations should equal the number of pump lines for which the flow rate needs to be calculated plus one additional unknown variable which is the pressure at the outlet of the system boundary. Using Gauss elimination one can solve these unknown variables representing the flow rate for the individual pump lines.

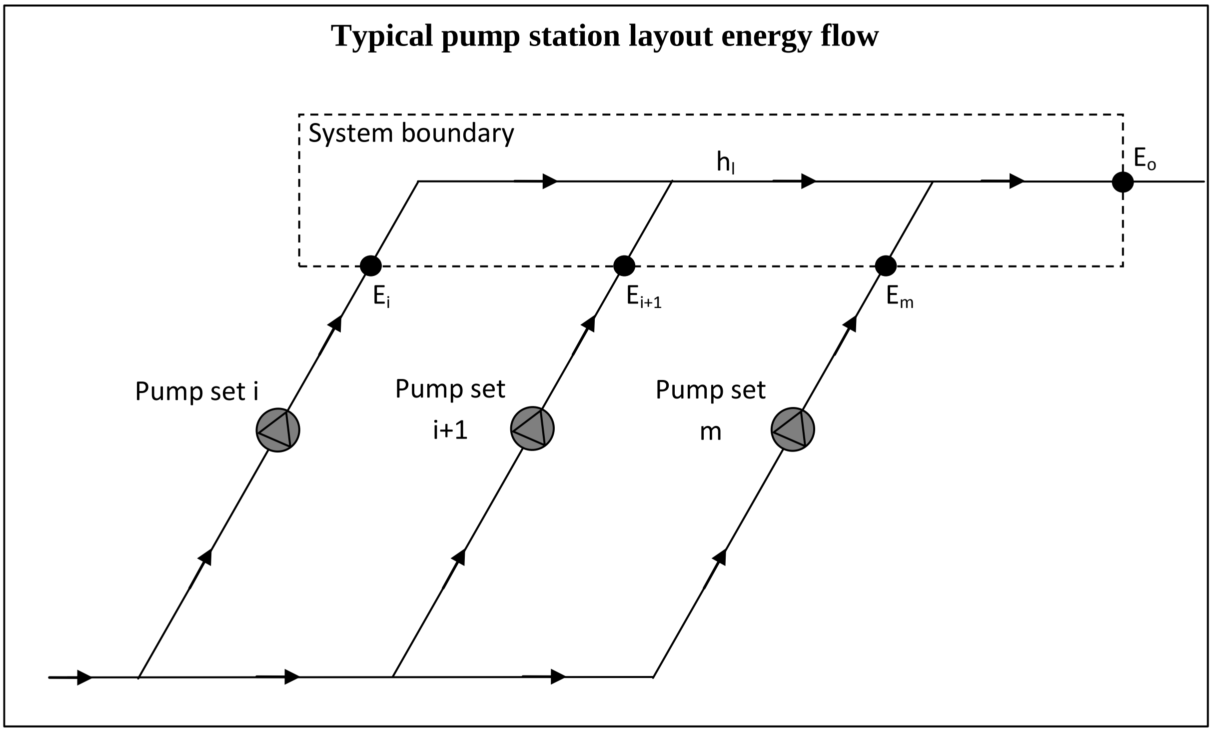


Figure 26: Typical pump station layout energy flow

Figure 26 is a diagrammatical representation of a pump station showing the individual pump lines of which the flow rate needs to be determined. The diagram also shows the system boundary around the delivery manifold of the pump station that is used to derive the equation used to calculate the flow rate of each pump line. The complete derivation of Equation 6 below used to calculate the individual flow rates is included in this dissertation in APPENDIX B.

**Equation 6**

$$\sum_{i=1}^{m}\left[\frac{P_i}{\rho g}+\frac{V_i^2}{2g}\right]=\frac{P_t}{\rho g}+\frac{V_t^2}{2g}+\sum K\frac{V^2}{2g}$$

With:

P - pressure

ρ - fluid density

g - gravitational acceleration 9.81 m/s$^2$

V - flow velocity

K - minor loss coefficient

## 3.4 Predicting the efficiency decay of a pump

To be able to predict the efficiency decay of a pump certain data is required. The data necessary is:

- The efficiency of the pump and,
- The operating hours of the pump.

In order to predict the efficiency decay of a pump, data over a long time span is required. What is seen as a long time span? For a pump's efficiency to decline, the components of the pump need to wear. Components like wear rings, bearings, seals, coatings, impeller and so forth needs to wear a fair amount to affect the efficiency of the pump. This wearing of components takes a certain amount of time. It could happen within months or even years, depending on the care taken during installation, commissioning and maintaining of the pump [31].

The efficiency decay of a pump can be represented by several algorithms. The most logical algorithm to predict the decay of a pump's efficiency would be an exponential curve with an initial value at time equals zero and with a negative slope at any time greater than zero. Another simpler, but less logical, algorithm to predict the decay of a pump's efficiency would be linear curve with an initial value at time equals zero and with a negative slope at any time greater than zero.

The formulas for both linear regression and exponential regression are given in Equation 7 and Equation 8 respectively.

**Equation 7**

$$\eta_s = a + bh \text{ [64]}$$

Where:

$$a = \frac{\sum \eta_s - b \sum h}{n} \text{ [64]}$$

$$b = \frac{n \sum (h\eta_s) - (\sum h)(\sum \eta_s)}{n \sum h^2 - (\sum h)^2} \text{ [64]}$$

With:

$\eta_s$ - pump set efficiency

a - the y-intercept of the graph

b - the slope of the graph
h - hours
n - the total number of data points

**Equation 8**

$$\eta_s = Ae^{Bh}[65]$$

Where:

$$B = \frac{S_{h\eta_s}}{S_{hh}}$$

$$A = e^{\overline{\ln \eta_s} - B\bar{h}}$$

$$S_{hh} = \frac{\sum h^2}{n} - \bar{h}^2$$

$$S_{\eta_s\eta_s} = \frac{\sum \ln {\eta_s}^2}{n} - \overline{\ln \eta_s}^2$$

$$S_{h\eta_s} = \frac{\sum h \cdot \ln \eta_s}{n} - \bar{h}\,\overline{\ln \eta_s}$$

$$\bar{h} = \frac{\sum h}{n}$$

$$\overline{\ln \eta_s} = \frac{\sum \ln \eta_s}{n}$$

With:

$\eta_s$ - pump set efficiency
a - the y-intercept of the graph
b - the slope of the graph
h - hours
n - the total number of data points

For each algorithm, linear and exponential regression, there is a correlation coefficient and a coefficient of determination that indicates the relevance of the predicting curve. The correlation coefficient, also known as the *Pearson product moment correlation coefficient*, measures the strength and the direction of a linear relationship between the two variables. The correlation coefficient ranges from -1 to 1 ($-1 \leq r \leq 1$) where zero represents no correlation and ±1 a perfect correlation. The positive or negative represents a linear upward or linear downward slope respectively. Guidelines for interpreting the coefficient of determination are given in Table 7 [66].

**Table 7: Guidelines for interpreting the coefficient of determination**

| Coefficient value | Interpretation |
|---|---|
| $0.7 < \lvert r \rvert \leq 1$ | Strong correlation |
| $0.4 < \lvert r \rvert < 0.7$ | Moderate correlation |
| $0.2 < \lvert r \rvert < 0.4$ | Weak correlation |
| $0 \leq \lvert r \rvert < 0.2$ | No correlation |

The coefficient of determination gives the proportion of the variance of the one predictable variable from the other variable. Its value ranges from 0 to 1 ($0 \leq r^2 \leq 1$). The value of the coefficient is a measure of how well the regression line represents the data. The coefficient of determination represents the percent of the data that is the closest to the line of best fit [66].

The methods for calculating the correlation coefficient for linear regression and exponential regression are given in Equation 9 and Equation 10 respectively. The coefficient of determination is calculated by squaring the correlation coefficient.

**Equation 9**

$$r = \frac{n\sum h\eta_s - (\sum h)(\sum \eta_s)}{\sqrt{n(\sum h^2) - (\sum h)^2}\sqrt{n(\sum \eta_s^2) - (\sum \eta_s)^2}} \text{ [66]}$$

With:

$r$ - correlation coefficient
$\eta_s$ - pump set efficiency
$h$ - hours
$n$ - the total number of data points

**Equation 10**

$$r = \frac{S_{h\eta_s}}{\sqrt{S_{hh}}\sqrt{S_{\eta_s\eta_s}}} \text{ [65]}$$

Where:

$$S_{h\eta_s} = \frac{\sum h \cdot \ln \eta_s}{n} - \bar{h}\,\overline{\ln \eta_s}$$

$$S_{hh} = \frac{\sum h^2}{n} - \bar{h}^2$$

$$S_{\eta_s\eta_s} = \frac{\sum \ln {\eta_s}^2}{n} - \overline{\ln \eta_s}^2$$

With:

| | | |
|---|---|---|
| r | - | correlation coefficient |
| $\eta_s$ | - | pump set efficiency |
| h | - | hours |
| n | - | the total number of data points |

## 3.5 Energy consumed due to pump system efficiency decay

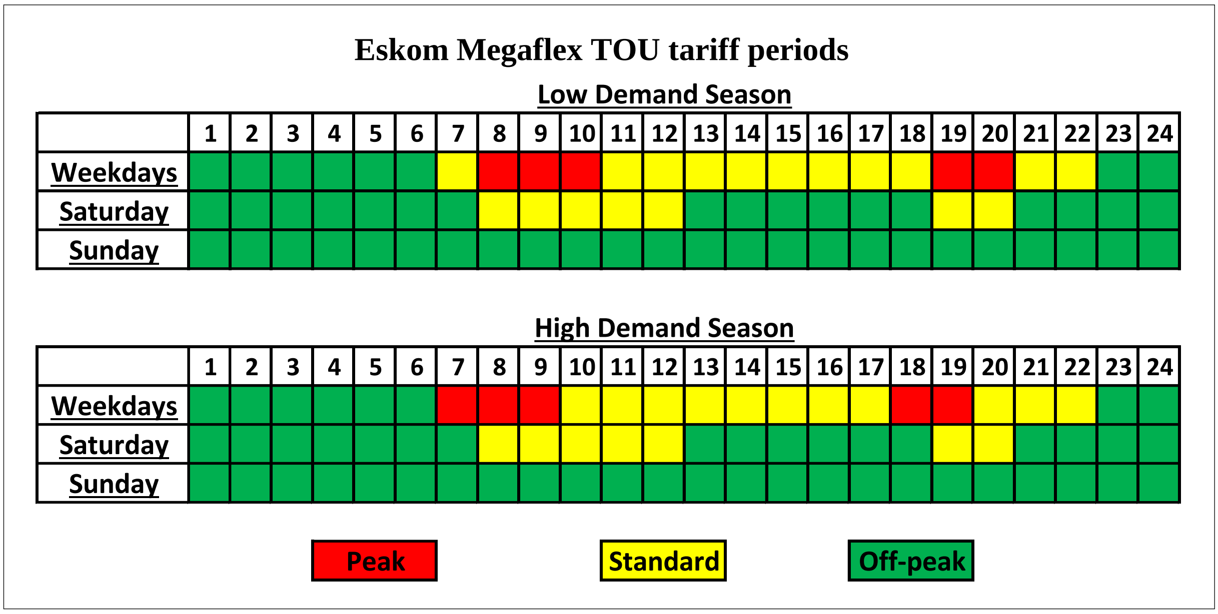
When the efficiency decay of a pump is known, the excessive operational costs for delivering the demand to the consumer can be calculated.

A decay in the efficiency of a pump results in the pump not being able to deliver its designed duty point. Increasing tolerances due to wear within the pump cause an increase in recirculation of the fluid within the pump which results in a lower flow rate from the pump. This lower flow rate due to efficiency decay means that the pump will have to operate longer hours to deliver a set demand. These longer operating hours result in an increase in operational costs for delivering the set demand.

When a set demand is unknown and the additional operational costs need to be calculated, a new set point needs to be determined. This was done in this study. The set point for the purpose of this study is a continuous operational time of five years. Also, for the purpose of this study, the flow rate from the pump was kept constant. The result is, due to the efficiency decay of the pump, the power consumed by the pump set will increase in order to maintain a constant flow rate from the pump. In reality, the opposite will occur. The power consumed by the pump set will remain constant while the flow rate from the pump will decrease.

### 3.5.1 Cumulative additional cost

Eskom uses a TOU tariff structure. The time slots for this structure are shown in Figure 27. The clients are billed according to this structure. The structure is divided into low demand season and high demand season. The respective seasons are divided into weekdays, Saturday and Sunday, and a day is divided into peak, standard and off-peak periods. Between the low demand season and the high demand season, the only difference is the time of the peak period. The peak period is shifted one hour earlier in the high demand season. The amount of peak, standard and off-peak periods remain the same in both the high and low demand seasons.



**Eskom Megaflex TOU tariff periods**

**Low Demand Season**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Weekdays** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟥 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟩 | 🟩 |
| **Saturday** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 |
| **Sunday** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

**High Demand Season**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Weekdays** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 |
| **Saturday** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 |
| **Sunday** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

🟥 Peak 🟨 Standard 🟩 Off-peak

**Figure 27: Eskom Megaflex TOU tariff periods**

In this study, as mentioned, the set point is continuously operating on the pumps for a period of five years. Due to the continuous operation it does not make any difference if the low or high demand season is used for the calculations. The amount of peak, standard and off-peak periods remain the same regardless of the season used. The tariffs for the respective seasons and periods of the days is given by the Megaflex tariffs as set out in APPENDIX A. Within the Megaflex structure there are multiple charges. These charges are also mentioned in Table

8. Not all charges are taken into account for this study. Reasons for not taking the charges into account are also specified in Table 8.

**Table 8: Megaflex structure charges**

| **Charge** | **Taken into account?** | **Reason** |
|---|---|---|
| Active energy charge (c/kWh) | Yes | Active energy means the units of energy consumed to perform the physical work. Active energy is charged in c/kWh. |
| Public Holidays | No | In order to simplify the calculations for the operational costs, public holiday tariffs are not taken into account. The influence of not taking the holiday tariffs into account will have a negligible effect over the total time considered (five years) when comparing the CAC. |
| Transmission network charge (R/kVA/month) | Yes | It is assumed that the kVA usage of the pump stations remain constant throughout the month of use. Also, the power factor remains constant. This is also a fixed monthly charge. |
| Distribution network capacity charge (R/kVA/month) | Yes | It is assumed that the kVA usage of the pump stations remain constant throughout the month of use. Also, the power factor remains constant. This is also a fixed monthly charge. |
| Distribution network demand charge (R/kVA/month) | Yes | It is assumed that the kVA usage of the pump stations remain constant throughout the month of use. Also, the power factor remains constant. This is also a fixed monthly charge. |
| Urban low voltage subsidy charge (R/kVA/month) | No | N/A (for the voltage range of 500V to 66kV this charge is R0.00). |
| Ancillary service charge (c/kWh) | Yes | The charge of ancillary services are in c/kWh and can be easily included in the operational costs calculations although it will have a negligible effect on the costs (<1%). |
| Service charge (R/account/day) | No | The amount paid for service charge per month, compared to the amount paid for the active energy per month, is negligibly small (<1%) and will not have a substantial effect on the operational costs when included in the calculations. |

| | | |
|---|---|---|
| Administration charge (R/POD/day) | No | The amount paid for administration charge per month, compared to the amount paid for the active energy per month, is negligibly small (<0.5%) and will not have a substantial effect on the operational costs when included in the calculations. |
| Reactive energy charge (c/kVArh) | Yes | This charge is only considered in the high demand season. In the low demand season the charge is 0 c/kVArh. |
| Electrification and rural network subsidy charge (c/kWh) | Yes | |
| Affordability subsidy charge (c/kWh) only payable by non-local authority tariffs | Yes | Only payable by non-local authority tariffs. |

Assumptions made in the operational cost calculations are as follows:

- The notified maximum demand (NMD) for all pump stations considered are greater than 1 MVA. In the case of the NMD being smaller than 1 MVA, another Eskom tariff structure will be used for calculating the operational costs.

- It is assumed that all the pump stations in this study fall under the non-local authority tariffs. In the case where pump stations fall under the local authority tariffs, the relevant tariffs structure should be used.

- It is assumed that no NMD exceedance occur that will incur excess network capacity charges.

- It is assumed that all Eskom power supply points at all the pump stations are within the range of 500V to 66kV.

- It is assumed that the power factor stays constant for all electrical motors.

## Calculating the operational cost

An example of a possible power usage structure for a pump station over a full week duration is shown in Figure 28. On the same graph, the electricity cost tariff structure for the low demand season is also shown. Depending on the demand, the power usage curve may vary from week to week. The tariff structure curve remains constant except for high demand seasons where the tariffs increase as per APPENDIX A.

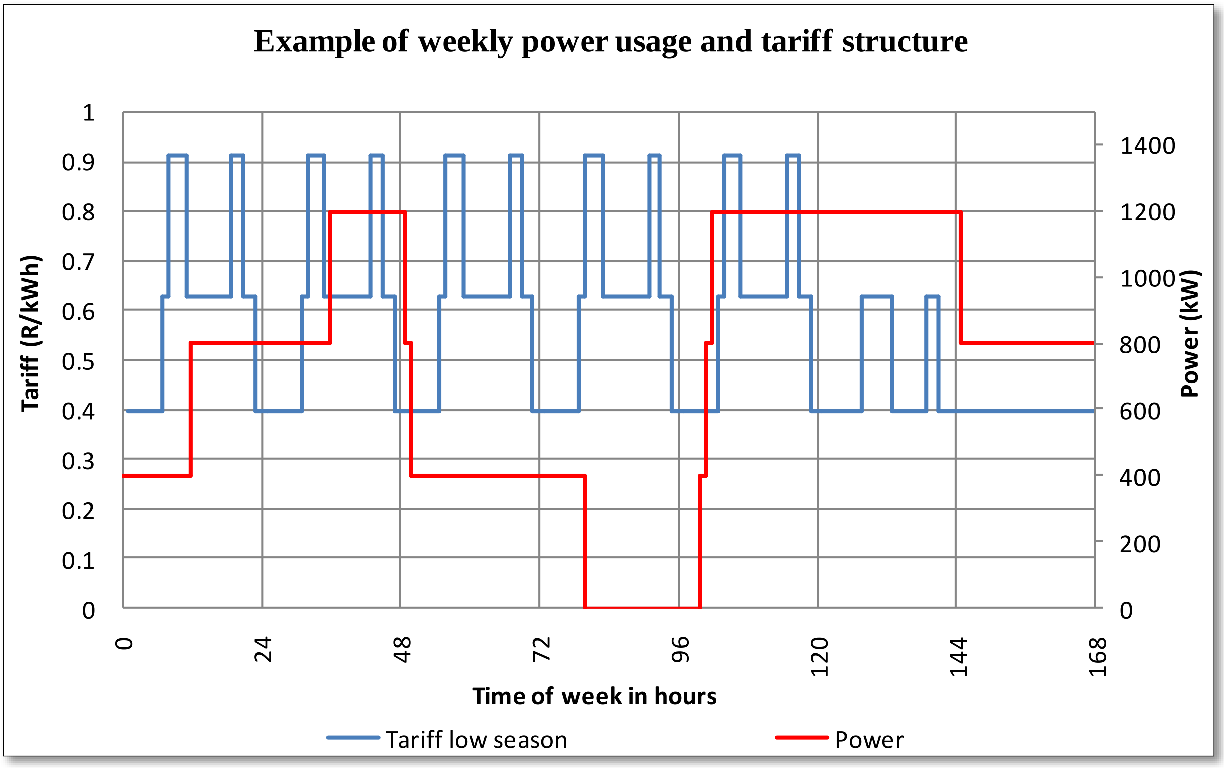


Figure 28: Example of possible pump station power usage and tariffs structure per week

The power consumed by the pump system is a function of time and of the efficiency of the pump system at the specific time. The tariff is a function of time and all the electricity charges taken into consideration as shown in Table 8. By recording the power consumed at each time step (the time step magnitude can be defined as deemed appropriate for the specific application) and knowing the tariff at the corresponding time step, the sum of the product of the power and the tariff from time zero to the end gives the total operational cost per week. This equation is given in Equation 11.

**Equation 11**

$$Cost\ per\ week = \sum_{j=0}^{l} \left[ P_{h_j}(\eta_s, P_t, t) \times R_j(t, A, T, C, D, Re, An, S, As) \right]$$

With:

$P_{hj}$ - hydraulic power at time step j

$P_t$ - total power

t - time

l - total amount of

$\eta_s$ - pump set efficiency

$R_j$ - cost at time step j

A - active energy charge

T - transmission network charge

C - network capacity charge

D - network demand charge

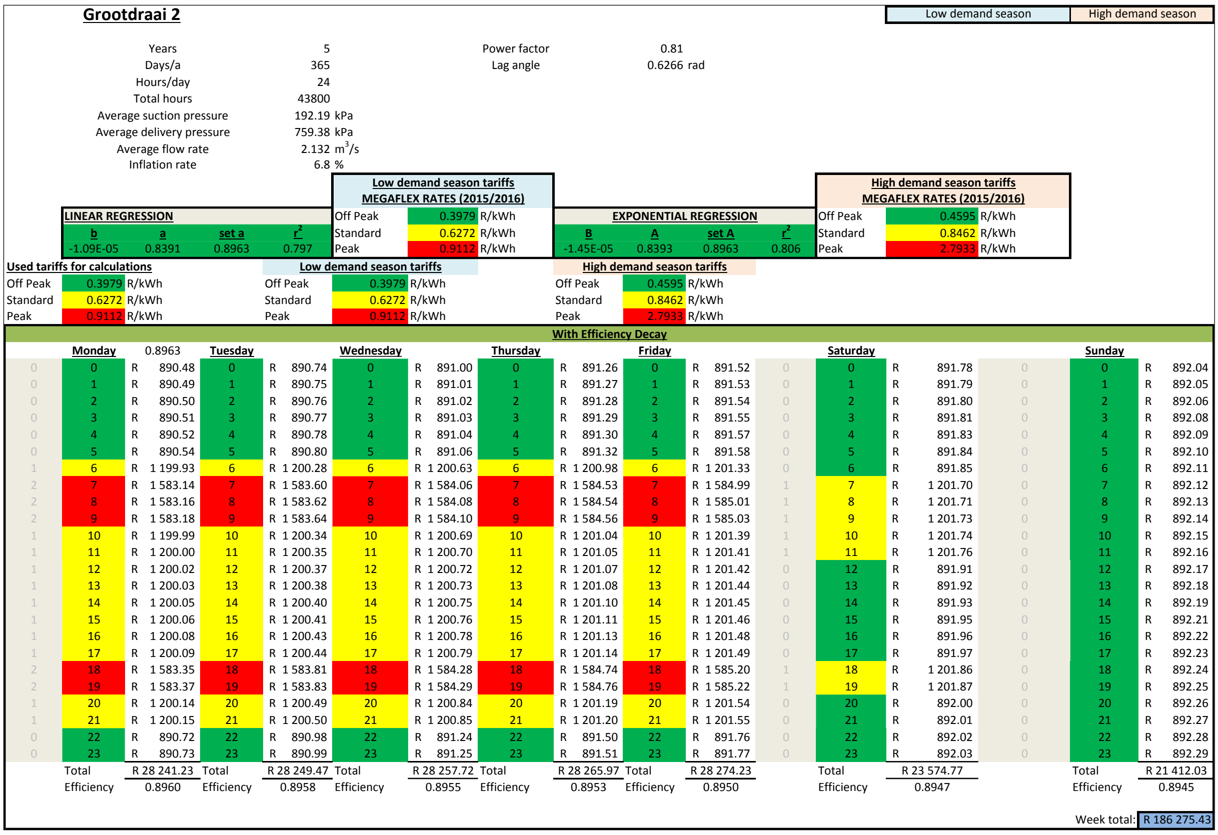
Re - reactive energy charge

An - ancillary service charge

S - electrification & rural network subsidy charge

As - affordability subsidy charge

Figure 29 shows an example of the spreadsheet used to calculate the weekly operational cost of a pump system taking into account the hourly efficiency decay.



**Grootdraai 2**

| Low demand season | High demand season |
|---|---|

| | | |
|---|---|---|
| Years | 5 | |
| Days/a | 365 | |
| Hours/day | 24 | |
| Total hours | 43800 | |
| Average suction pressure | 192.19 | kPa |
| Average delivery pressure | 759.38 | kPa |
| Average flow rate | 2.132 | $m^3/s$ |
| Inflation rate | 6.8 | % |

| | | |
|---|---|---|
| Power factor | 0.81 | |
| Lag angle | 0.6266 | rad |

**LINEAR REGRESSION**

| b | a | set a | $r^2$ |
|---|---|---|---|
| -1.09E-05 | 0.8391 | 0.8963 | 0.797 |

**Low demand season tariffs**
**MEGAFLEX RATES (2015/2016)**

| | | |
|---|---|---|
| Off Peak | 0.3979 | R/kWh |
| Standard | 0.6272 | R/kWh |
| Peak | 0.9112 | R/kWh |

**EXPONENTIAL REGRESSION**

| B | A | set A | $r^2$ |
|---|---|---|---|
| -1.45E-05 | 0.8393 | 0.8963 | 0.806 |

**High demand season tariffs**
**MEGAFLEX RATES (2015/2016)**

| | | |
|---|---|---|
| Off Peak | 0.4595 | R/kWh |
| Standard | 0.8462 | R/kWh |
| Peak | 2.7933 | R/kWh |

**Used tariffs for calculations**

| | | |
|---|---|---|
| Off Peak | 0.3979 | R/kWh |
| Standard | 0.6272 | R/kWh |
| Peak | 0.9112 | R/kWh |

**Low demand season tariffs**

| | | |
|---|---|---|
| Off Peak | 0.3979 | R/kWh |
| Standard | 0.6272 | R/kWh |
| Peak | 0.9112 | R/kWh |

**High demand season tariffs**

| | | |
|---|---|---|
| Off Peak | 0.4595 | R/kWh |
| Standard | 0.8462 | R/kWh |
| Peak | 2.7933 | R/kWh |

**With Efficiency Decay**

| | Monday | 0.8963 | Tuesday | | Wednesday | | Thursday | | Friday | | | Saturday | | | Sunday | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | R 890.48 | 0 | R 890.74 | 0 | R 891.00 | 0 | R 891.26 | 0 | R 891.52 | 0 | 0 | R 891.78 | 0 | 0 | R 892.04 |
| 0 | 1 | R 890.49 | 1 | R 890.75 | 1 | R 891.01 | 1 | R 891.27 | 1 | R 891.53 | 0 | 1 | R 891.79 | 0 | 1 | R 892.05 |
| 0 | 2 | R 890.50 | 2 | R 890.76 | 2 | R 891.02 | 2 | R 891.28 | 2 | R 891.54 | 0 | 2 | R 891.80 | 0 | 2 | R 892.06 |
| 0 | 3 | R 890.51 | 3 | R 890.77 | 3 | R 891.03 | 3 | R 891.29 | 3 | R 891.55 | 0 | 3 | R 891.81 | 0 | 3 | R 892.08 |
| 0 | 4 | R 890.52 | 4 | R 890.78 | 4 | R 891.04 | 4 | R 891.30 | 4 | R 891.57 | 0 | 4 | R 891.83 | 0 | 4 | R 892.09 |
| 0 | 5 | R 890.54 | 5 | R 890.80 | 5 | R 891.06 | 5 | R 891.32 | 5 | R 891.58 | 0 | 5 | R 891.84 | 0 | 5 | R 892.10 |
| 1 | 6 | R 1 199.93 | 6 | R 1 200.28 | 6 | R 1 200.63 | 6 | R 1 200.98 | 6 | R 1 201.33 | 0 | 6 | R 891.85 | 0 | 6 | R 892.11 |
| 2 | 7 | R 1 583.14 | 7 | R 1 583.60 | 7 | R 1 584.06 | 7 | R 1 584.53 | 7 | R 1 584.99 | 1 | 7 | R 1 201.70 | 0 | 7 | R 892.12 |
| 2 | 8 | R 1 583.16 | 8 | R 1 583.62 | 8 | R 1 584.08 | 8 | R 1 584.54 | 8 | R 1 585.01 | 1 | 8 | R 1 201.71 | 0 | 8 | R 892.13 |
| 2 | 9 | R 1 583.18 | 9 | R 1 583.64 | 9 | R 1 584.10 | 9 | R 1 584.56 | 9 | R 1 585.03 | 1 | 9 | R 1 201.73 | 0 | 9 | R 892.14 |
| 1 | 10 | R 1 199.99 | 10 | R 1 200.34 | 10 | R 1 200.69 | 10 | R 1 201.04 | 10 | R 1 201.39 | 1 | 10 | R 1 201.74 | 0 | 10 | R 892.15 |
| 1 | 11 | R 1 200.00 | 11 | R 1 200.35 | 11 | R 1 200.70 | 11 | R 1 201.05 | 11 | R 1 201.41 | 1 | 11 | R 1 201.76 | 0 | 11 | R 892.16 |
| 1 | 12 | R 1 200.02 | 12 | R 1 200.37 | 12 | R 1 200.72 | 12 | R 1 201.07 | 12 | R 1 201.42 | 0 | 12 | R 891.91 | 0 | 12 | R 892.17 |
| 1 | 13 | R 1 200.03 | 13 | R 1 200.38 | 13 | R 1 200.73 | 13 | R 1 201.08 | 13 | R 1 201.44 | 0 | 13 | R 891.92 | 0 | 13 | R 892.18 |
| 1 | 14 | R 1 200.05 | 14 | R 1 200.40 | 14 | R 1 200.75 | 14 | R 1 201.10 | 14 | R 1 201.45 | 0 | 14 | R 891.93 | 0 | 14 | R 892.19 |
| 1 | 15 | R 1 200.06 | 15 | R 1 200.41 | 15 | R 1 200.76 | 15 | R 1 201.11 | 15 | R 1 201.46 | 0 | 15 | R 891.95 | 0 | 15 | R 892.21 |
| 1 | 16 | R 1 200.08 | 16 | R 1 200.43 | 16 | R 1 200.78 | 16 | R 1 201.13 | 16 | R 1 201.48 | 0 | 16 | R 891.96 | 0 | 16 | R 892.22 |
| 1 | 17 | R 1 200.09 | 17 | R 1 200.44 | 17 | R 1 200.79 | 17 | R 1 201.14 | 17 | R 1 201.49 | 0 | 17 | R 891.97 | 0 | 17 | R 892.23 |
| 2 | 18 | R 1 583.35 | 18 | R 1 583.81 | 18 | R 1 584.28 | 18 | R 1 584.74 | 18 | R 1 585.20 | 1 | 18 | R 1 201.86 | 0 | 18 | R 892.24 |
| 2 | 19 | R 1 583.37 | 19 | R 1 583.83 | 19 | R 1 584.29 | 19 | R 1 584.76 | 19 | R 1 585.22 | 1 | 19 | R 1 201.87 | 0 | 19 | R 892.25 |
| 1 | 20 | R 1 200.14 | 20 | R 1 200.49 | 20 | R 1 200.84 | 20 | R 1 201.19 | 20 | R 1 201.54 | 0 | 20 | R 892.00 | 0 | 20 | R 892.26 |
| 1 | 21 | R 1 200.15 | 21 | R 1 200.50 | 21 | R 1 200.85 | 21 | R 1 201.20 | 21 | R 1 201.55 | 0 | 21 | R 892.01 | 0 | 21 | R 892.27 |
| 0 | 22 | R 890.72 | 22 | R 890.98 | 22 | R 891.24 | 22 | R 891.50 | 22 | R 891.76 | 0 | 22 | R 892.02 | 0 | 22 | R 892.28 |
| 0 | 23 | R 890.73 | 23 | R 890.99 | 23 | R 891.25 | 23 | R 891.51 | 23 | R 891.77 | 0 | 23 | R 892.03 | 0 | 23 | R 892.29 |
| | Total | R 28 241.23 | Total | R 28 249.47 | Total | R 28 257.72 | Total | R 28 265.97 | Total | R 28 274.23 | | Total | R 23 574.77 | | Total | R 21 412.03 |
| | Efficiency | 0.8960 | Efficiency | 0.8958 | Efficiency | 0.8955 | Efficiency | 0.8953 | Efficiency | 0.8950 | | Efficiency | 0.8947 | | Efficiency | 0.8945 |
| | | | | | | | | | | | | | | | Week total: | R 186 275.43 |

Figure 29: Example of a weekly cost calculation spreadsheet considering efficiency decay

The operational cost calculations are done on a weekly basis in which the cost is calculated hourly. The total operational cost for the week is recorded and the calculation for the next week is started. For each hour of the week the efficiency of the pump set is calculated using the efficiency decay per hour for the specific pump. The efficiency at the end of a week's cost calculation is carried forward and used as the initial starting efficiency for the following week.

The efficiency decay calculated as described in Section 3.4 is given in percentage per hour (%/hour) and is denoted by coefficient b in Equation 7. A negative coefficient denotes a decay in efficiency. Calculating the cost per week requires calculating the corresponding efficiency at the corresponding time. Equation 12 is used to calculate the efficiency at a specific time of the day granted the efficiency of the pump set is known at the beginning of the day.

**Equation 12**

$$\eta_{s(t)} = \eta_{s(t=0)} + b(\Delta t)$$

With:

$\eta_s$ - efficiency of the system

b - efficiency decay

t - time

$\Delta t$ - differential time

In order to calculate the CAC, due to the effect of efficiency decay on the pump system, the cost of operating the pump system has to be calculated without taking into account the effect of the efficiency decay. Ultimately the sum of the difference in operational cost at each respective corresponding time and between the two respective calculations, with efficiency decay and without, is known as the CAC.

### 3.5.2 Performance indicators

Performance indicators are useful indicators to present the effectiveness of the pump system. Numerous performance indicators exists for measuring the performance of a pump system. The performance indicator for a pump system should be monitored continuously. The continuous monitoring and analysing of the performance indicator helps to reflect the decay in effectiveness of the pump system or the progress made in maintaining the pump system [25][28].

The performance indicator used in this study is called the PEI. It is calculated as follows and was developed by F. Papa and D. Radulj [25].

**Equation 13**

$$PEI = kWh/Mm^3/m$$

The indicator is a measure of the amount of energy consumed to deliver a unit amount of water per unit amount of head produced. The average manufacturer PEI is 3350 at BEP. A pump with a PEI greater than 4000 kWh/$Mm^3$/m is considered to underperform significantly [25].

### 3.5.3 Calculating maintained cumulative additional cost

In order to quantify the effect that the efficiency decay of a pump has on operating costs, the MCAC is determined. Excessive efficiency decay is a result of poor maintenance or lack thereof. Implementing good maintenance practice, as discussed in Chapter 2 of this dissertation, will ensure that the average efficiency of a pump will remain close to the designed efficiency of the pump.

The MCAC is calculated by setting predetermined criterion. This criterion, based on the literature review done in Chapter 2, is to allow the efficiency of a pump to decrease by a set amount. According to literature in Chapter 2, the efficiency gain that can be achieved by doing regular maintenance such as replacement of damaged bearings or replacement of wear rings is within the range of 4% - 8%. Greater efficiency gains are possible, but these cases require more extreme maintenance or even refurbishment. The decision was made for the purpose of this study to allow for an average efficiency decrease of 8%.

The method used for calculating the CAC in Section 3.5.1 was used to calculate the MCAC. However, in calculating the MCAC, the efficiency of the pump system was allowed to decrease by about 8% only. The direct decrease in efficiency was not used to simulate the decay, the PEI described in Section 3.5.2 was used to simulate the efficiency decay. The program was written such that the PEI of the pump system will be reset to the original PEI once the limit is reached in order to simulate the effects of implementing proper maintenance on the pump system. The pump system PEI was programmed to not exceed 3350 kWh/Mm$^3$/m as described in Section 3.5.2.

## 3.6 Conclusion

In this chapter the acquisition of data from various pump stations were described. The data was obtained from manually entered logbooks. Due to the nature of the research done it was impossible to generate new data within the available time frame.

The method used for calculating the efficiency of each pump set is the conventional method. Certain constraints could exist such as not knowing the flow rate through the specific pump. In some cases only one flow meter could be installed at a pump station measuring the total flow rate from the pump station. A method was formulated to calculate the flow rate of the specific pump through Gauss elimination.

After calculating the efficiency of a pump, the efficiency decay was predicted by making use of linear regression. The formulas for predicting the efficiency decay through linear regression were given. Guidelines for interpreting the results of a predicted efficiency decay were tabulated.

The CAC due to the decay of a pump's efficiency were formulated and calculated over a period of five years of continuous operation. The charges included in the calculation were tabulated and the formulas for calculating the operational cost were formulated. The PEI was introduced which was used to determine the maintenance interval for a simulated maintained pump. The MCAC was calculated.

# CHAPTER 4

## Assessment of energy consumption results

*Chapter 4*

*In Chapter 4 the four case studies which consist of fourteen individual pump sets are presented. The effect of maintaining a relatively high pump set efficiency is illustrated for each individual pump set.*

# 4 ASSESSMENT OF ENERGY CONSUMPTION RESULTS

## 4.1 Introduction

Up to this point, the problem of energy consumption of bulk water pump systems has been identified. Energy prices in South Africa have gone up drastically and any means where the saving of energy can be realised will not only benefit the consumer on capital savings, but also the country. Most importantly, the environment will benefit from these energy savings.

In Chapter 2 a study was done on how centrifugal pumps and induction motors work and by what means the energy consumption of these equipment could be reduced. Equipment such as monitoring systems which will assist in making informed decisions on reducing the energy consumption of pump systems were introduced.

Along with monitoring systems, good maintenance structures are required which should be implemented correctly and on time to be able to attain the possible energy savings. Different types of maintenance structures exists and the most popular structure used to minimise the maintenance costs and energy consumption is known as CBM.

Finally, in Chapter 2 a literature review was done on savings that were realised by others once the correct maintenance structures were implemented. Savings of 3% - 30% can be realised if the system is managed and maintained correctly.

In Chapter 3, the method that was used to simulate the potential savings that can be achieved once the literature in Chapter 2 is implemented on the bulk water supply systems, is described.

In this chapter the results simulating the maintenance done on bulk water pump systems will be looked at. The results will reflect what possible energy savings can be realised after a continuous period of five years.

The first pump from case study one is discussed in detail. Each following pump is not discussed in such detail, although, the highlights of the specific pump is discussed in detail.

At the end of this chapter a summary of the results of all the pumps are given for comparison which will ease the comparison of the individual pumps.

## 4.2 Overview of pump station data

In order to verify the data used during the analysis of the effects of maintenance and decaying pump efficiency, a wide range of data sources and pumping systems were obtained. Data was obtained from a large number of individual pump sets in order to ensure that deviations in electronic monitoring system's and mechanical monitoring system's accuracy is eliminated during the analysis. Fourteen different pump sets from five different pumping systems were considered. Table 9 shows a summary of the data obtained for each pump set.

**Table 9: Pump sets data summary**

| Pump set | Data time period (hours) | Pump set operating hours | No. data points | Installed capacity (kW) |
|---|---|---|---|---|
| GD1 | 40992 | 16600 | 21 | 1650 |
| GF2 | 25200 | 15430 | 27 | 2150 |
| GF3 | 80496 | 38269 | 45 | 2150 |
| GF4 | 15480 | 8273 | 17 | 2150 |
| GF5 | 49872 | 18589 | 40 | 2150 |
| TU1b | 46752 | 28204 | 36 | 320 |
| TU1m | 46752 | 28204 | 36 | 1405 |
| HH1b | 25992 | 2707 | 13 | 1232 |
| HH1m | 25992 | 2707 | 13 | 1683 |
| HH2b | 107736 | 16566 | 57 | 1232 |
| HH2m | 107736 | 16566 | 57 | 1683 |
| HH3b | 170880 | 23758 | 73 | 1232 |
| HH4b | 113952 | 10171 | 24 | 1232 |
| HH4m | 113952 | 10171 | 24 | 1683 |

To ensure that the data that was analysed was consistent, long periods of time were considered. The data obtained from the different pump sets were recorded over various time spans at regular intervals over periods spanning multiple years of operation. In so doing, long periods of standby time and extended maintenance events caused by seasonal changes in water demand and redundancy were also considered in the analysis.

Considering the extended periods of time and the multiple pump sets, the possibility for human error during the recording of the data was also eliminated. The data was recorded by different operators, during different shifts and extending further than employment periods. The data was not recorded by a single operator which contributes to minimising human error.

### 4.2.1 Data set outliers

A pumping system in a steady state condition does not show sharp deviations from initial operating conditions. Immediate discontinuities from the steady state condition, therefore, represents an error and with that an outlier that should be removed from the data set. Additionally, any change in operating characteristics can be attributed to either failure of the system components (sluggish control or reflux valves or failure of valve actuators or air valves) or a change in the operating state (a large off-take is added to the rising main). The outliers that are removed from the data set are attributed to one or more of the following:

- Faulty sensors

Faulty sensors can cause incorrect readings when initial calibration settings were not done. The accuracy of the sensor deviates from its initial calibration with time and re-calibration of the sensor is periodically required. If the sensor is not re-calibrated as frequently as required, faulty readings will be recorded. If sensor failure is not detected, the readings obtained from the sensor will also show an immediate, sharp deviation from the correct values. These deviations are often not recognised by operating personnel and incorrect readings are recorded.

- Change in fluid dynamics

Extreme system pressure spikes that exceed the rated values of sensors will cause sensor failure or de-calibration. If such an event is not detected by operators, incorrect data is recorded. Sensor failure can also cause data loss. In the event of data captured during or directly after a dynamic change in the state of the system (pump start-up, valve closure or throttle, pump shut down), surge conditions will result in incorrect readings. After a dynamic change, a time period is required for the system to reach a steady state before any data can be recorded.

- Human error

Human record data error could occur, such as reading the value incorrectly. The data can be printed in the logbook under the incorrect heading. Operators are able to recognise a trend in the data and instead of physically taking the readings from the instruments, they copy previous data into following time slots. Data for a specific pump set can be recorded into the wrong logbook.

- Component failures

A component that fails to operate in its designed state will result in system characteristics deviations. These deviations in flow rate or pressure will not represent the correct actual pump set operation. If the component failure is not recognised and rectified, this causes a number of successive outliers. Examples of component failure includes sticky valves, actuator failures, air valve failures, leakages, blockages or malicious damage.

- Human intervention to change system characteristics

Maintenance events, reconditioning of mechanical components or calibration of sensors will result in a permanent change in the pump set characteristics (reconditioning of a pump improves pumping efficiency). These occurrences will show a step in the recorded data set.

Outliers found in the recorded data throughout the case studies are removed before the pump sets efficiency decay is assessed.

## 4.3 Case study 1: Grootdraai pump station

Figure 30: Grootdraai pump station

The first case study done is on Grootdraai pump station and consists of only one pump in the study. Grootdraai pump station is situated at Grootdraai Dam in Mpumalanga, South Africa. Grootdraai pump station consists of four large horizontal split casing centrifugal pumps manufactured by Sulzer. The installed motor capacity per pump line is 1650 kW. Data for only one pump was available. This was for pump number 2. No logbooks for pump 1, 3 and 4 could be obtained.

Figure 31 shows the processed data collected for Grootdraai pump number 2. Depicted in this graph is the efficiency of the pump calculated using the differential pressure across the pump, the flow rate through the pump and the power consumption by the electrical motor. The efficiency is plotted against the operating hours of the pump.

As seen in the graph, there is a period from approximately 3000 to 12000 hours where no data was available. Although no data was available for this period of approximately 9000 hours, the pump seems to have still been operational. This is evident as a decay in the efficiency continued to exist.

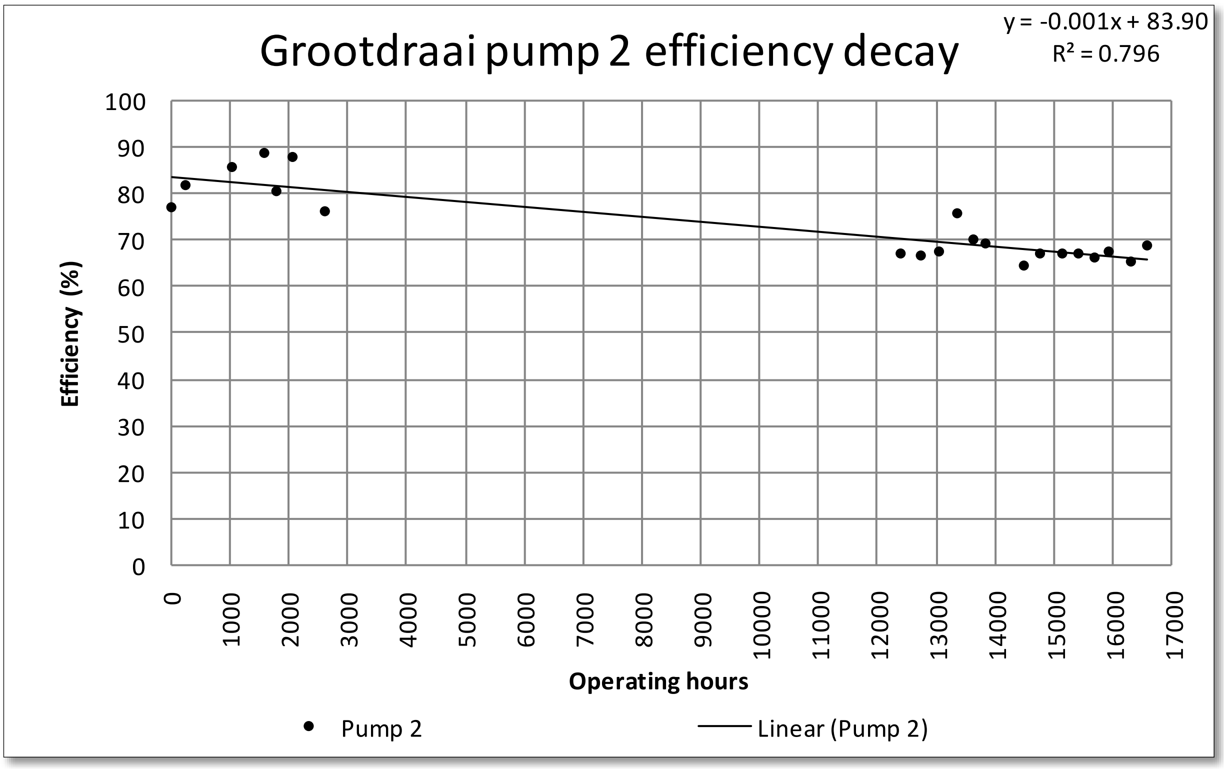


Figure 31: Grootdraai data collected

A linear regression line was plotted using all the data points. The formula for this linear regression is shown on the graph for reference. The R-squared value for the linear regression is 0.796 which represents a very good estimation of the data. The gradient of the regression line represents the efficiency decay of the pump system.

The exact value for the gradient of the linear regression line was calculated using the formulas presented in Chapter 3 Section 3.4 and adapted to represent the percentage decay per 10000 operating hours. The efficiency decay for Grootdraai pump number 2 was calculated to be 10.895 %/(hour x $10^4$).

From the data collected, the y-intercept on the graph which represents the efficiency of a newly installed pump is calculated to be 83.91%. This value was ignored and the actual efficiency of this specific pump was obtained from Sulzer using the model number of the pump. For simulation purposes, the calculations were done as if the pump was newly installed. Operational cost calculations were then calculated from there on.

**Table 10: Grootdraai pump no. 2 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1650 | 16600 | 0.796 | 89.63 | 10.895 |

With the initial pump manufactured efficiency known and the rate of efficiency decay known, the unmaintained efficiency of the pump can be plotted versus the operating hours of the pump. The time over which the efficiency was plotted is a complete period of five years which equates to 43680 hours. The unmaintained efficiency decay is represented by the red line in Figure 32. The CAC of an unmaintained pump was calculated by making use of this efficiency line.

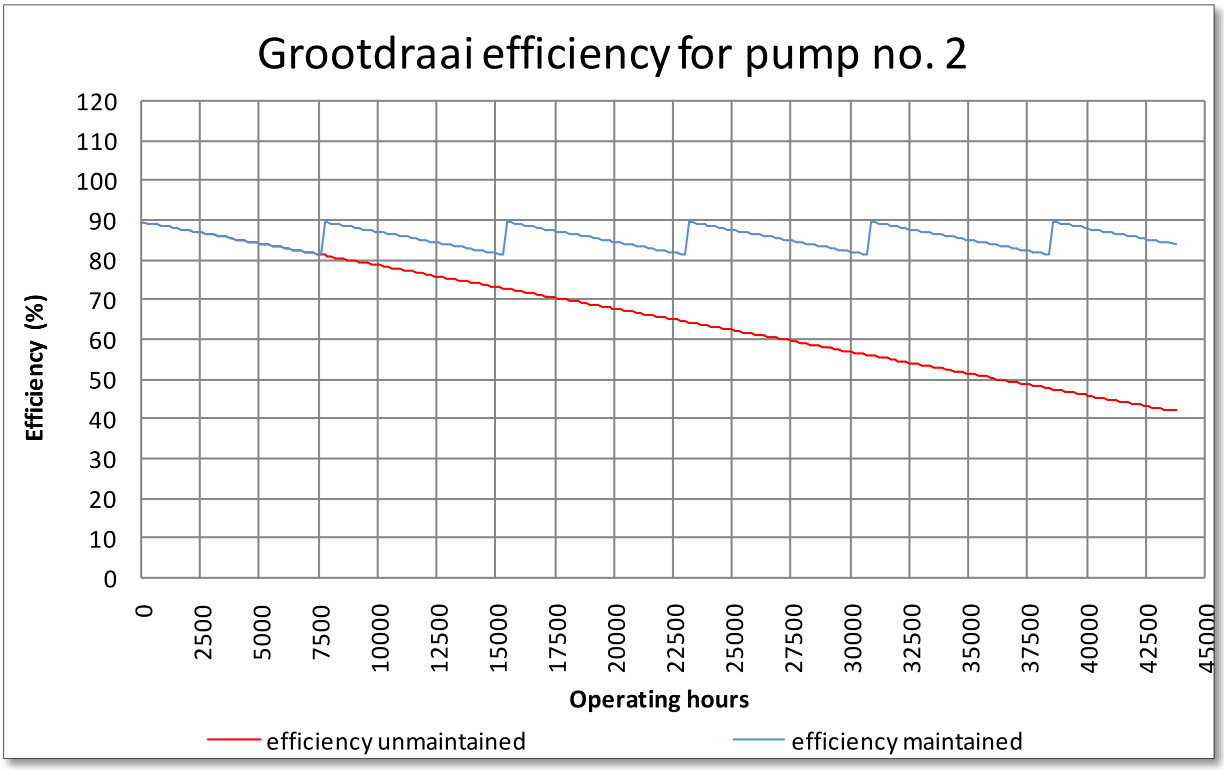


Figure 32: Grootdraai efficiency comparison

Together with the unmaintained pump efficiency line a maintained pump efficiency curve was plotted on the same graph in Figure 32 represented by the blue line. By using the PEI described in Chapter 3 Section 3.5.2, the PEI of the pump was allowed to increase to a maximum of 3350 kW/Mm$^3$/m, which represents the PEI at BEP, as the efficiency decreases. The initial PEI of the pump was 3043 kW/Mm$^3$/m.

When a PEI of 3350 kW/Mm$^3$/m was reached, the efficiency of the pump was reset to its initial efficiency value. With an efficiency decay rate as shown in Table 10, this resulted in a maintenance interval of 7728 hours after which the appropriate maintenance as described in Chapter 2 of this dissertation should be followed to restore the efficiency of the pump to its initial value. The maintained efficiency line was used to calculate the MCAC.

In Figure 33, the CAC of an unmaintained pump was plotted against the MCAC of a maintained pump. The operating costs were calculated as if the pump was fully operational for a complete period of five years which is equal to 43680 hours.

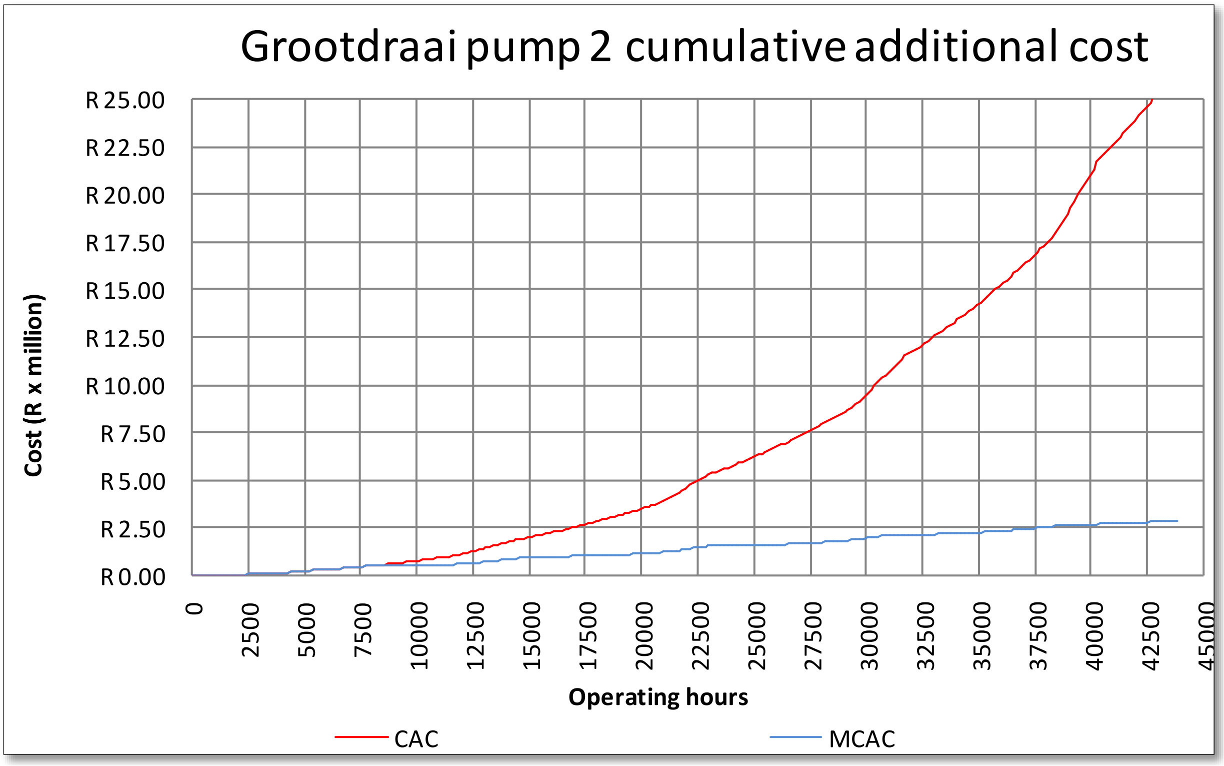


**Figure 33: Grootdraai energy cost comparison**

As seen in Figure 33, the CAC increases exponentially. Along with the increase, steps exist where the rate of increase is greater than the rest of the graph. Seen in these sections, where the rate of increase is greater than the rest of the graph, are due to the high demand season where the electricity prices are considerably higher than the rest of the year. The same is seen on the MCAC graph.

It is evident from Figure 33 that there is a vast difference in the CAC of an unmaintained pump and the CAC of a maintained pump. In this case, the difference in cost over a five year period is R 23 436 050 which equates to a saving of 89.07%. The CAC can never equate to zero as there will always be a decay in the efficiency of a pump. Although, by maintaining the pump and increasing the efficiency regularly, this will result in minimising the CAC. Table 11 shows the saving that is result of minimising the CAC.

**Table 11: Grootdraai pump no. 2 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3043 | 7728 | 26 311 425 | 2 875 375 | 89.07 |

## 4.4 Case study 2: Tutuka pump station

**Figure 34: Tutuka pump station**

The second case study is done on Tutuka pump station and a total of two pumps will be discussed in this case study. Tutuka pump station is situated at Grootdraai Dam in Mpumalanga, South Africa and supplies water to Tutuka power station. Tutuka pump station consists of four pump lines. Each pump line consists of a booster pump and a high lift pump. The pumps are all horizontal split casing centrifugal pumps manufactured by Mather and Platt (currently known as Sulzer). The installed motor capacity per pump line is 320 kW for the booster pump and 1405 kW for the high lift pump.

Only the data obtained from pump line number 1 was usable. Logbooks for pump line number 2 could not be obtained. Data for pump line 3 and 4 was obtained, but the quality of the data was of such a nature that it could not be used for this study. The data for pump lines 3 and 4 is presented in APPENDIX C.

### Tutuka booster pump number 1

The first pump from Tutuka pump station is the booster pump of pump line number 1. The data obtained for this pump is shown in Figure 35. The right hand side set of data is the full set of data collected for the specific pump including the outliers. These points result in a low R-squared value of 0.317. After deleting as few as possible of the outliers, the data on the left hand side was obtained with a R-squared value of 0.797 which is acceptable to use.

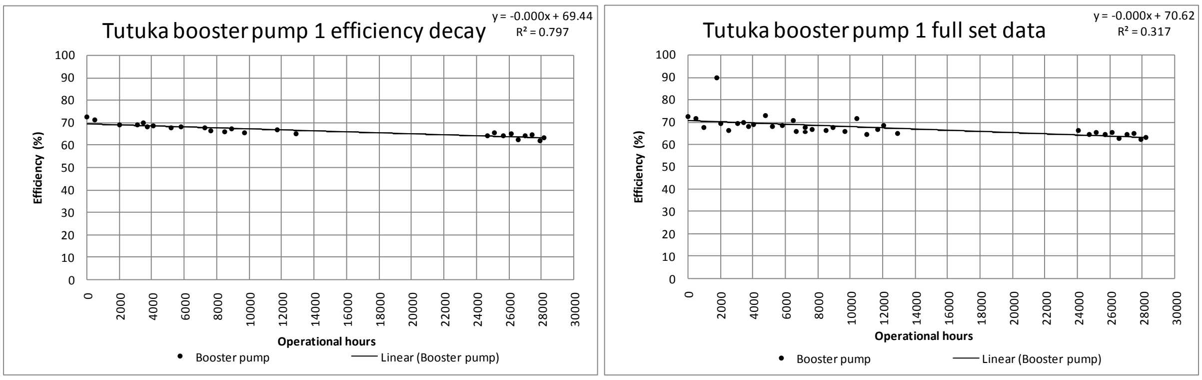


**Figure 35: Tutuka booster pump no. 1 data collected**

Due to the lack of any maintenance data from this pump set it is not possible to exactly determine the cause of the outliers. Although, when visually inspecting the data in the right hand side it is clear that there are a couple of outliers that could have been caused by reasons as discussed in section 4.2.1 in this chapter. The point to the far right were not seen as outliers due to the trendline plotted shows that the decrease in efficiency continued over the period between 13000 and 24000 hours.

The same procedure was followed to explain the results for the pump in case study one was followed for the two pumps in case study two. The summary of results given in the tables will be given for each pump discussed in the remainder of the study. The data collected for the Tutuka booster pump number 1 is summarised in Table 12 below.

**Table 12: Tutuka booster pump no. 1 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 320 | 28200 | 0.797 | 88.77 | 2.221 |

Figure 36 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump.

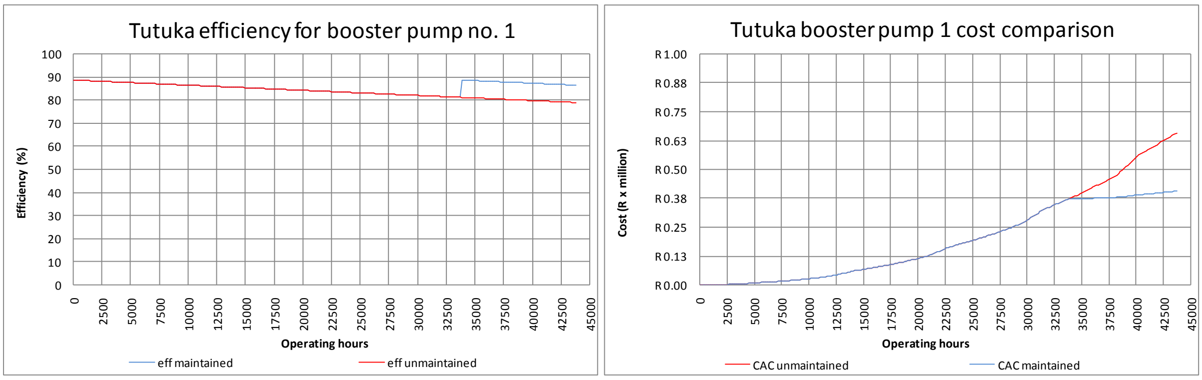


**Figure 36: Tutuka booster pump no. 1 efficiency and energy cost comparison**

**Table 13: Tutuka booster pump no. 1 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3068 | 33936 | 656 731 | 406 720 | 38.07 |

As seen in Table 12 the efficiency decay of this pump is very low, 2.221%/hour x $10^4$. This very low decay in efficiency resulted in only one maintenance interval over a period of five years which is at 33936 hours. Due to the poor quality of the data obtained from this specific pump set, the results cannot be used as an absolute result for this specific pump.

### Tutuka main pump number 1

The second pump from Tutuka pump station is the main pump of pump line number 1. The data obtained for this pump is shown in Figure 37. The right hand side set of data is the full set of data collected for the specific pump including the outliers. Seen in this right hand graph is a period of time between approximately 13000 and 24000 hours where no data was available. Plotting a trendline across the entire set of data, it is evident that an increase in efficiency exists from the one period to the other. However, when only considering the data from 0 to 13000 hours and removing a couple of outliers, a noticeable decay in the efficiency is evident as seen in the left hand graph.

It was not possible to determine the specific reason for the outliers. As discussed in section 4.2.1 of this chapter a pumping system in a steady state condition should not show sharp deviations (outliers) from initial operating conditions. To continue with the study, as with other pump sets, a visual inspection was made of the data points and points that deviate from the rest of the data was considered an outlier and removed. Once again the cause of the outlier can be attributed to one or several of the reasons as discussed in section 4.2.1 of this chapter.

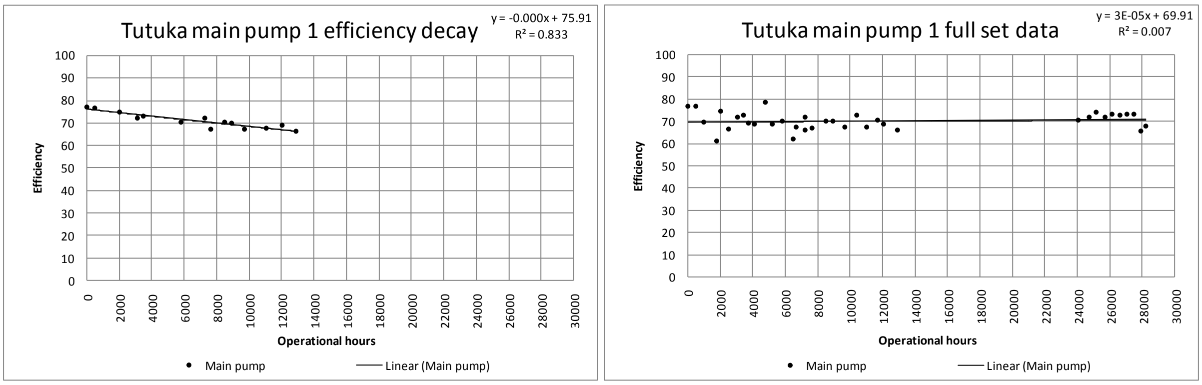


Figure 37: Tutuka main pump no. 1 data collected

The cause for the increase in efficiency of the pump system could not be obtained from the data and due to the lack of maintenance data. However, this increase in efficiency could be due to human intervention when changing system characteristics. The data collected for the Tutuka main pump number 1 is summarised in Table 14 below.

**Table 14: Tutuka main pump no. 1 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1405 | 13000 | 0.833 | 88.77 | 7.516 |

Figure 38 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump.

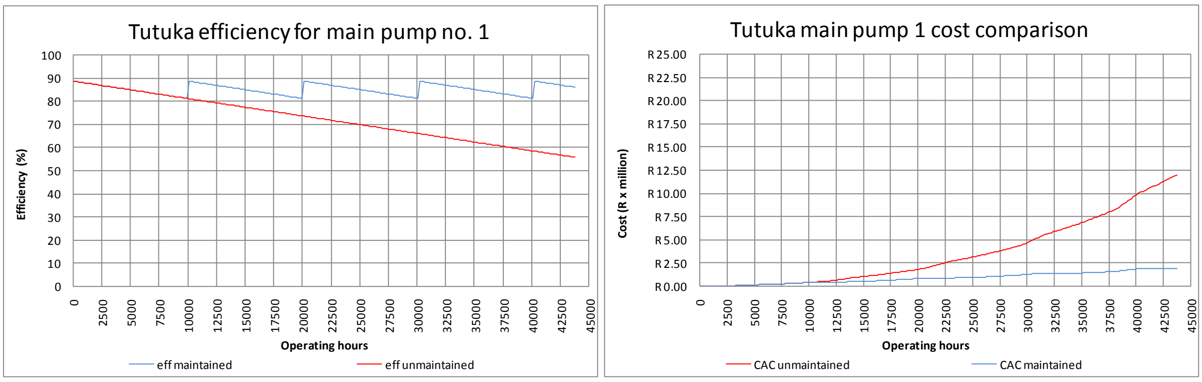


**Figure 38: Tutuka main pump no. 1 efficiency and energy cost comparison**

**Table 15: Tutuka main pump no. 1 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3071 | 10080 | 11 935 671 | 1 937 251 | 83.77 |

As seen in Table 15, possible saving of 83.77% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation. Due to the poor quality of the data obtained from this specific pump set, the results cannot be used as an absolute result for this specific pump.

## 4.5 Case study 3: Grootfontein pump station

**Figure 39: Grootfontein pump station**

The third case study done is on Grootfontein pump station which includes a total of four pump sets. Grootfontein pump station is situated in Mpumalanga, South Africa and receives its water from Grootdraai pump station via a canal. Grootfontein pump station consists of four pump lines in the original station and a newer fifth pump line in a separate building adjacent to the original building. The pumps are all horizontal split casing centrifugal pumps manufactured by Sulzer. The installed motor capacity per pump line 2150 kW.

Data for pump line number 1 could not be obtained. Data for pump line 2 through 5 was collected from the logbooks kept on site and used in this case study.

### Grootfontein pump number 2

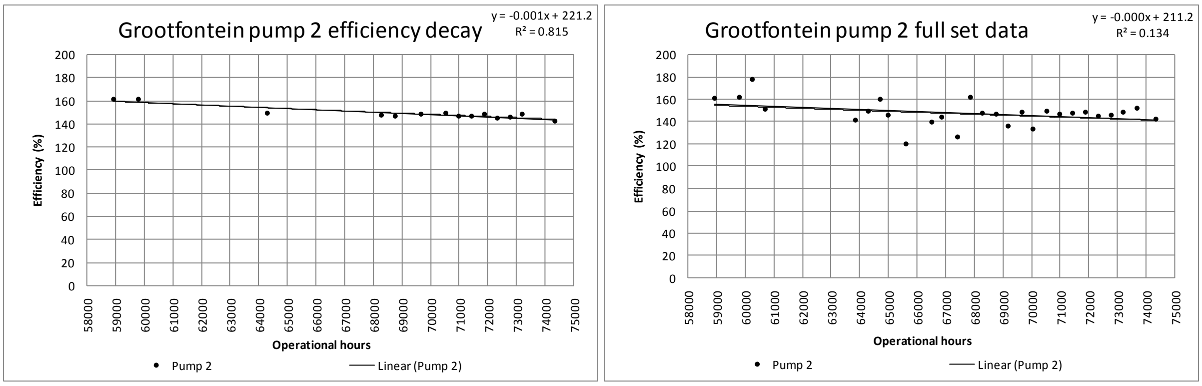


Figure 40: Grootfontein pump 2 data collected

As in the previous case studies, the original collected data is shown in the right hand graph and the used data is shown in the left hand graph. From a visual inspection of the data in the right hand side it can be seen between 70000 and 75000 hours that the data follows a good trend and that there does not outliers does not exist. Before 70000 hours the data is very scattered.

The definite reasons for these outliers could not be determined due to the lack of any additional data on the pump set. However, the cause of these outliers could be attributed to the reasons as discussed in section 4.2.1 of this chapter. In order to continue with the study outliers were deleted to obtain a good R-squared value. This procedure was followed for all four pump sets.

As seen in the graphs, the efficiency of the pump system ranges between 140% and 160%. It is impossible for a pump system to have an efficiency of 100% or above due to conservation of energy and losses within the system. All the calculations done in this dissertation were checked and these results shown here are correct. The reason for these high efficiencies calculated from the data collected could be due to wrongly calibrated sensors or the like.

Although the magnitude of the efficiency calculated for this pump is incorrect, a clear decay in the efficiency of the pump system is still clearly visible. For this reason the data was still used but the initial efficiency value for a newly manufactured pump was used in the calculations. The summary of the data for Grootfontein pump set 2 is given in Table 16. A discussion of the rest of the pump sets' data and graphs can be found in APPENDIX C.

**Table 16: Grootfontein pump no. 2 data**

| Pump no. | Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|---|
| 2 | 2150 | 15400 | 0.815 | 88.77 | 10.412 |

In Table 16 it is noted that the data total hours only account for 15400 hours. The simulation below in Figure 41 extrapolates the data in Table 16 to 45000 hours. This extrapolation is not necessarily accurate, but it is good representation of what the pump set efficiency possibly could undergo. Figure 41 shows the comparison of the efficiency and energy costs for an unmaintained and maintained Grootfontein pump number 2.

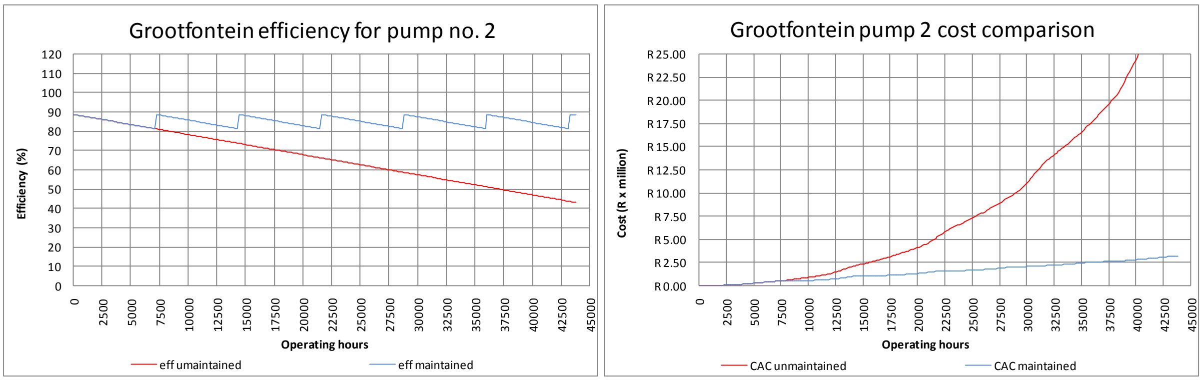


**Figure 41: Grootfontein pump no. 2 efficiency and energy cost comparison**

**Table 17: Grootfontein pump no. 2 savings**

| Pump no. | Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|---|
| 2 | 3072 | 7224 | 30 359 468 | 3 180 903 | 89.52 |

As seen in Table 17, possible saving of 89.52% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation. Due to the poor quality of the data obtained from this specific pump set, the results cannot be used as an absolute result for this specific pump.

## 4.6 Case study 4: Heyshope pump station

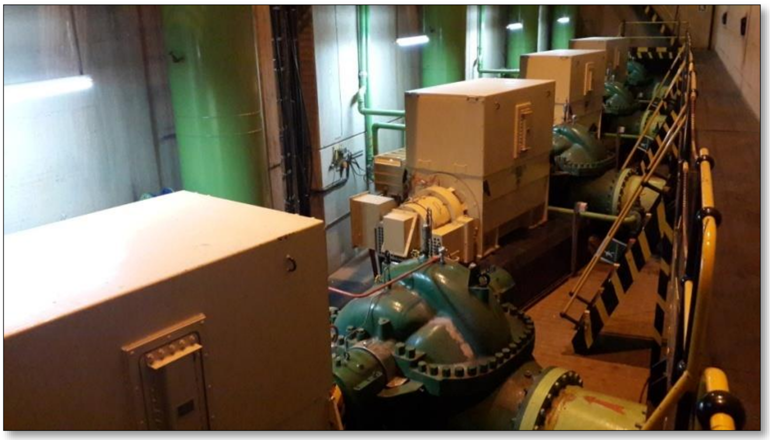


**Figure 42: Heyshope pump station booster pumps**

The fourth case study done is on Heyshope pump station and a total of seven pump sets will be discussed in this case study. Heyshope pump station is situated at Heyshope Dam in Mpumalanga, South Africa. Heyshope pump station consists of four pump lines. Each pump line consists of a booster pump and a high lift pump. The pumps are all horizontal split casing centrifugal pumps manufactured by Sulzer. The installed motor capacity per pump line is 1232 kW for the booster pump and 1683 kW for the high lift pump.

Data for all the pump sets were collected and all of the data was usable except for main pump number 3.

## Heyshope booster pump number 1

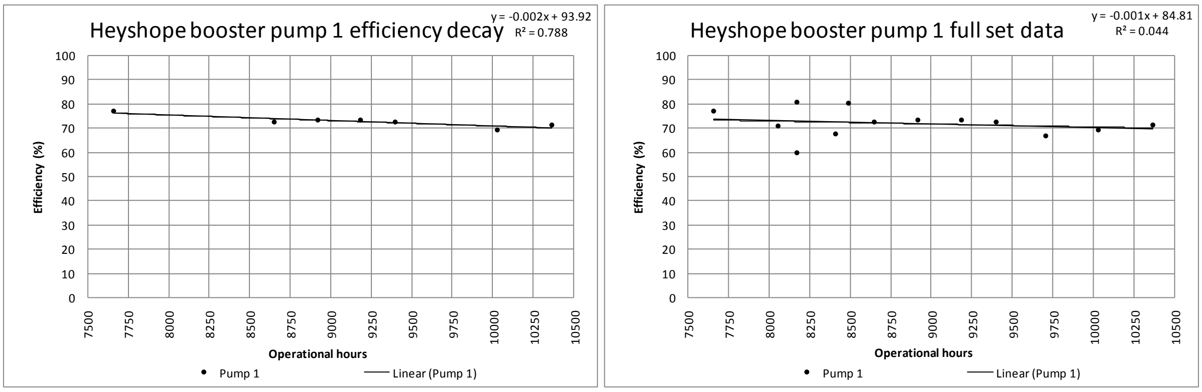


**Figure 43: Heyshope booster pump 1 data collected**

The data for Heyshope booster pump number 1 is shown in Figure 43. Between 8500 and 10500 hours the data seem to follow a reasonable trend. The data before 8500 hours is very scattered and the these points are considered to be outliers. Once again due to the lack of any additional data that could explain the reason for the outliers, these points are removed with reference to the reasons in section 4.2.1 of this chapter as the possible causes for the outliers.

Some outliers have been deleted to obtain a good R-squared value of 0.788. This procedure was followed for all seven pump sets. The range of data used shows a clear decay in efficiency. The summary of the data for Heyshope booster pump set 1 is given in Table 18. A discussion of the rest of the pump sets' data and graphs can be found in APPENDIX C.

**Table 18: Heyshope booster pump no. 1 data**

| Pump no. | Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|---|
| 1b | 1232 | 2700 | 0.788 | 90.3 | 22.948 |

In Table 18 it is noted that the data total hours only account for 2700 hours. The simulation below in Figure 44 extrapolates the data in Table 18 to 45000 hours. This extrapolation is not necessarily accurate, but it is good representation of what the pump set efficiency possibly could undergo. The same accounts for all the pumps within this study which was included in APPENDIX C

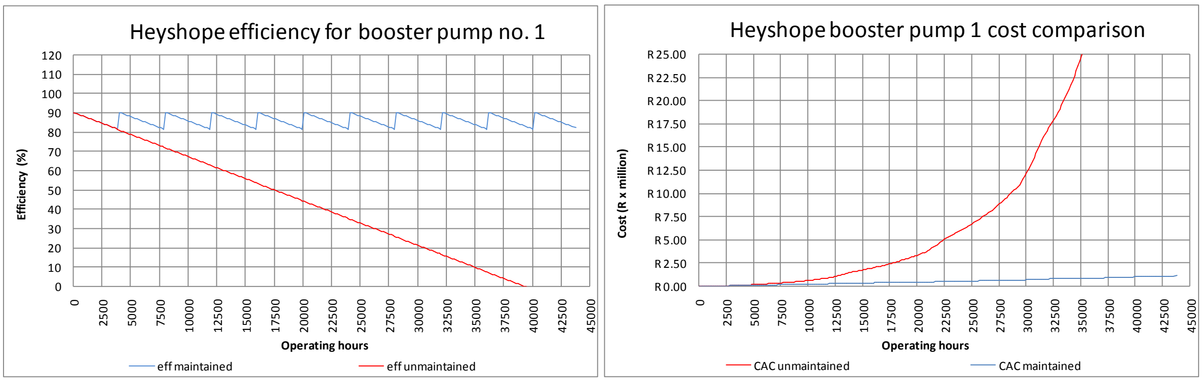


**Figure 44: Heyshope booster pump no. 1 efficiency and energy cost comparison**

Figure 44 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump. As seen in the graph displaying the efficiencies, this pump set has a very aggressive efficiency decay, such that after a continual decay the efficiency of the pump set reaches zero after 39269 hours. This is unrealistic as the pump will not continue to decay to a zero efficiency, instead it will fail long before this point is reached. However, the rate of efficiency decay was still used for this study.

**Table 19: Heyshope booster pump no. 1 savings**

| Pump no. | Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|---|
| 1b | 3028 | 4032 | 138 830 762 | 1 102 216 | 94.75 |

Seen in Table 19 are the possible savings that could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation. Due to the poor quality of the data obtained from this specific pump set, the results cannot be used as an absolute result for this specific pump.

## 4.7 Interpretation of results

All the results from the different case studies are summarised in Table 20.

**Table 20: Summary of case study results**

| Pump set | Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|---|
| GD1 | 3043 | 7728 | 26 311 425 | 2 875 375 | 89.07 |
| GF2 | 3072 | 7224 | 30 359 468 | 3 180 903 | 89.52 |
| GF3 | 3072 | 8568 | 29 551 945 | 3 995 429 | 86.48 |
| GF4 | 3072 | 9408 | 23 379 974 | 3 301 324 | 85.88 |
| GF5 | 3072 | 8400 | 38 255 096 | 5 056 436 | 86.78 |
| TU1b | 3068 | 33936 | 656 731 | 406 720 | 38.07 |
| TU1m | 3071 | 10080 | 11 935 671 | 1 937 251 | 83.77 |
| HH1b | 3028 | 4032 | 138 830 762 | 1 102 216 | 94.75 |
| HH1m | 3024 | 3360 | 30 149 423 | 3 616 449 | 88.00 |
| HH2b | 3018 | 15624 | 4 415 579 | 1 255 069 | 71.58 |
| HH2m | 3015 | 8400 | 23 270 199 | 2 784 919 | 88.03 |
| HH3b | 3021 | 8232 | 8 621 915 | 1 011 071 | 88.27 |
| HH4b | 3028 | 4032 | 154 238 238 | 1 035 305 | 97.32 |
| HH4m | 3029 | 2520 | 161 817 181 | 3 163 068 | 92.02 |

From the literature in this dissertation, it was mentioned that the average typical efficiency gain of a pump system by doing typical regular maintenance such as replacing oil, maintaining seals and occasionally replacing bearings, is approximately 8%. In the case studies, the limiting factor determining when the efficiency of the pump system should be reinstated to original stance, was the PEI as described in Chapter 3. It was mentioned in the literature that the average PEI of a new pump is around 3350 kW/Mm$^3$/m. The initial PEI of each pump in the cases of this dissertation is given in Table 21.

**Table 21: Pump set initial PEI**

| Pump set | Initial PEI (kW/Mm$^3$/m) |
|---|---|
| GD2 | 3043 |
| GF2 | 3073 |
| GF3 | 3072 |
| GF4 | 3071 |
| GF5 | 3072 |
| TU1b | 3068 |
| TU1m | 3071 |
| HH1b | 3028 |
| HH1m | 3024 |
| HH2b | 3018 |
| HH2m | 3015 |
| HH3b | 3021 |
| HH4b | 3028 |
| HH4m | 3029 |

As seen in the table, the initial PEI for each of these pump sets was just below 3100. It was decided that the PEI of each pump set will decay to 3350 after which the efficiency of the pump set is reset to its initially installed value. After performing the calculations of a maintained pump, the maximum efficiency decay of each pump was calculated. This maximum efficiency decay of each pump is shown in Table 22.

**Table 22: Maximum efficiency decay**

| Pump set | Maximum efficiency decay (%) |
|---|---|
| GD2 | 8.236 |
| GF2 | 7.347 |
| GF3 | 7.502 |
| GF4 | 7.429 |
| GF5 | 7.431 |
| TU1b | 7.500 |
| TU1m | 7.450 |
| HH1b | 8.867 |
| HH1m | 9.053 |
| HH2b | 9.034 |
| HH2m | 9.158 |
| HH3b | 9.032 |
| HH4b | 8.797 |
| HH4m | 8.784 |

As verification, it is seen that when letting a pump set's PEI decay from the initial value to the specified value of 3350, the efficiency decay of each pump is close to the mentioned 8% efficiency gain. The average efficiency decay of all the pump sets is 8.3%.

In this chapter, four case studies have been covered. Case study one consisted of one pump from Grootdraai pump station. Case study two consisted of two pumps from Tutuka pump station. Case study three consisted of four pumps from Grootfontein pump station and case study four consisted of seven pumps from Heyshope pump station. Each of the fourteen pumps' data have been processed and results were given for each pump in detail. In this section a summary of the fourteen pumps is given. However, due to the poor quality of the data obtained the results given further in this section cannot be taken as absolute results for each specific pump set.

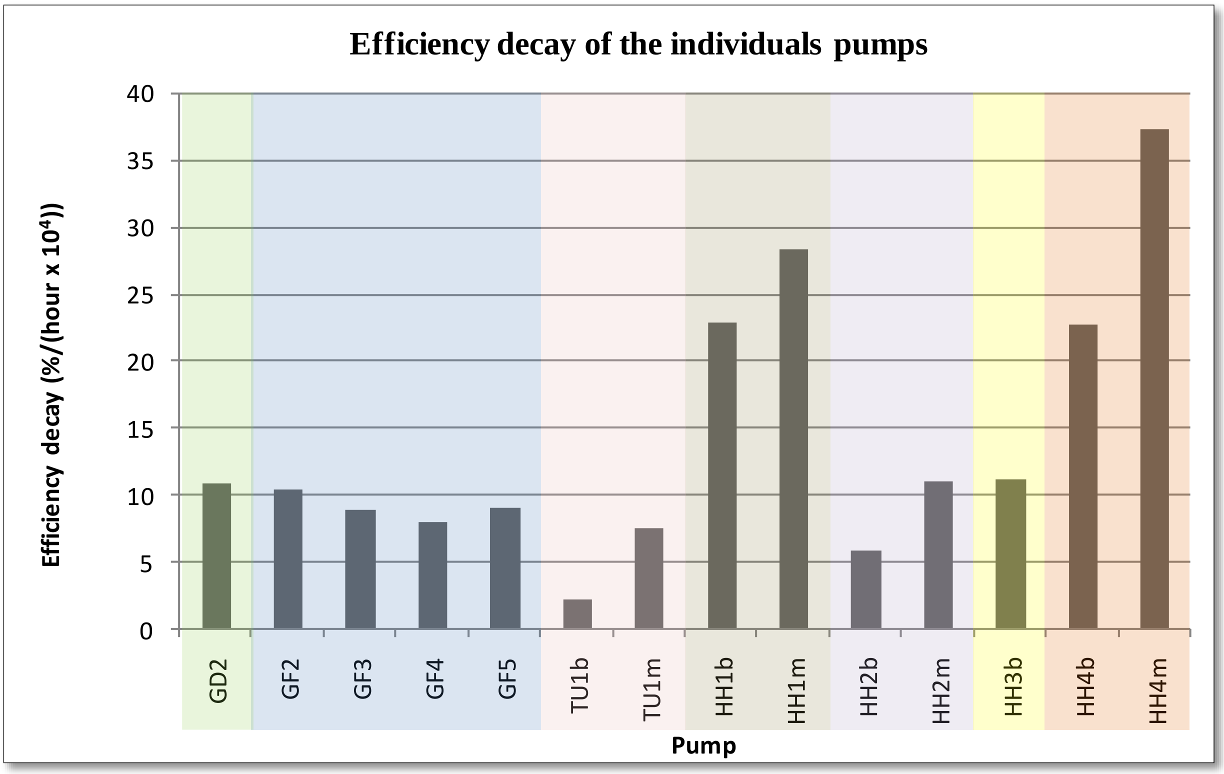


**Figure 45: Efficiency decay of the individual pumps**

Seen in Figure 45 is the rate at which the efficiency of the pump set decays. These values were calculated from the data obtained. There are four pump sets of which the efficiency decay is very high. The first two pumps with the high efficiency decay is pump line one at Heyshope pump station which consists of the booster pump one and main pump one. The second two pumps with the high efficiency decay is pump line four at Heyshope pump station which consists of the booster pump four and main pump four.

The reason for these four pumps having a very high efficiency decay is unknown. The high efficiency decay rate could be attributed to poor maintenance on these pumps. It could be that these pumps were installed incorrectly. It could be due to the quality of the water being pumped, although, this is ruled out due to the other pump sets in this pump station pumping the same water and these do not show the same rate of decay.

The remaining ten pumps all have a very similar efficiency decay rate with only one pump, TU1b, which has a very low efficiency decay rate. The average decay rate for these pumps is 8.52% every 10000 hours. The average decay rate for the remaining four pump sets with very high efficiency decays is 27.86% every 10000 hours. For the ten pumps and four pumps respectively, their average maintenance periods are 11760 and 3486 hours respectively. The maintenance periods for each pump set is shown in Figure 46.

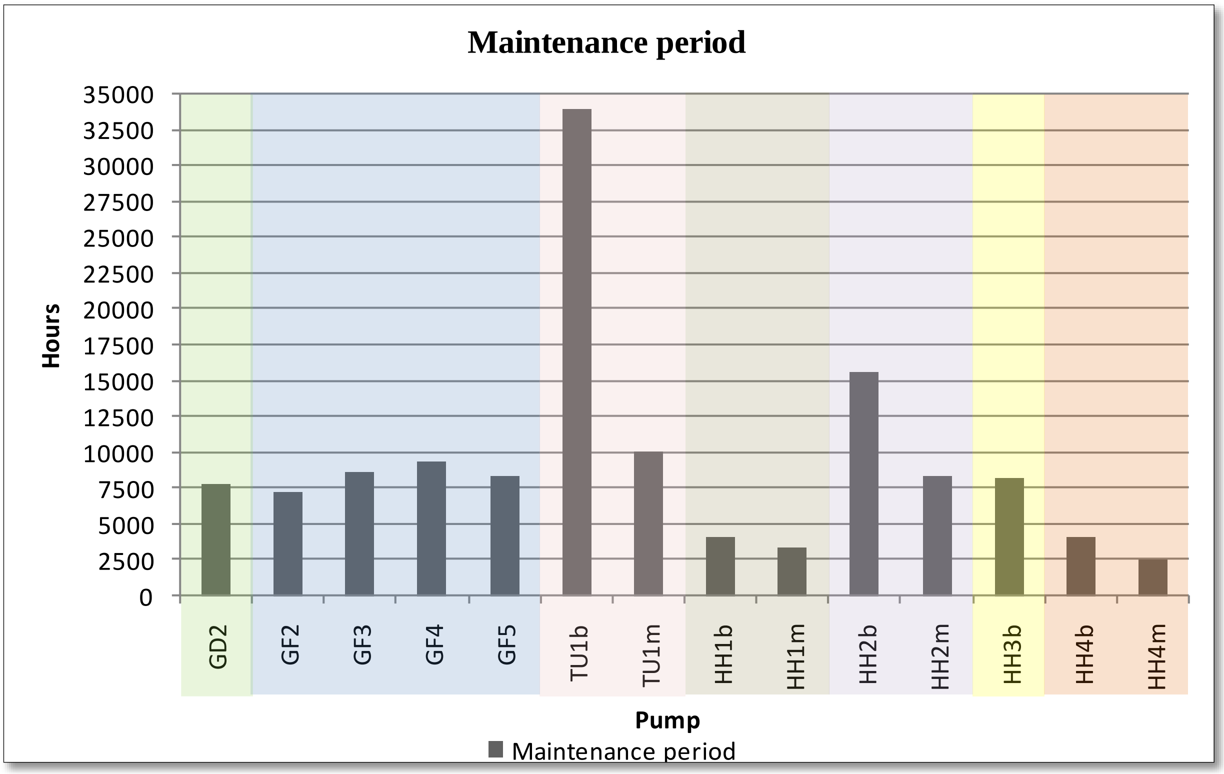


**Figure 46: Maintenance periods for each pump set**

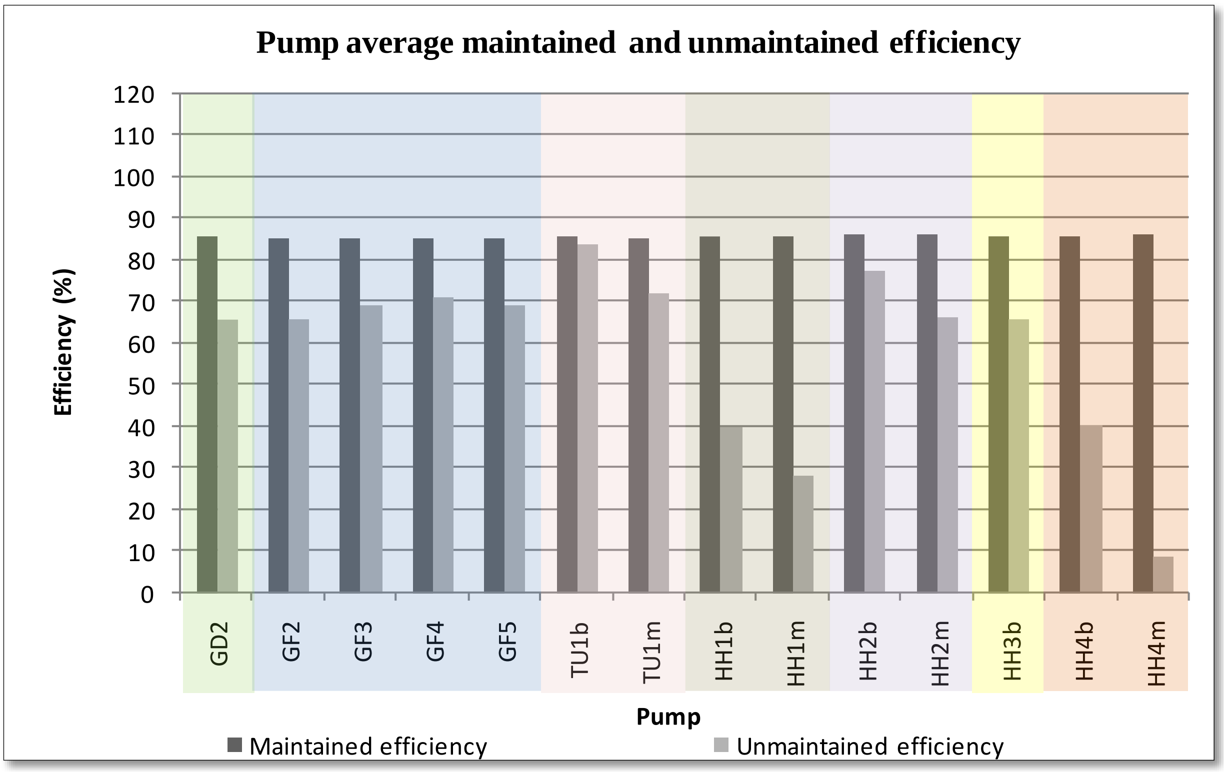


**Figure 47: Pump set average maintained and unmaintained efficiency**

Figure 47 shows each pump sets' average efficiency when the pump set is maintained and unmaintained. As seen in the figure, the average efficiency of all the pump sets remain high at 85.65% when the maintenance on the pump sets are simulated at each pump sets' maintenance interval. The unmaintained efficiency of the pump sets over the five years simulated are much lower than the average efficiency.

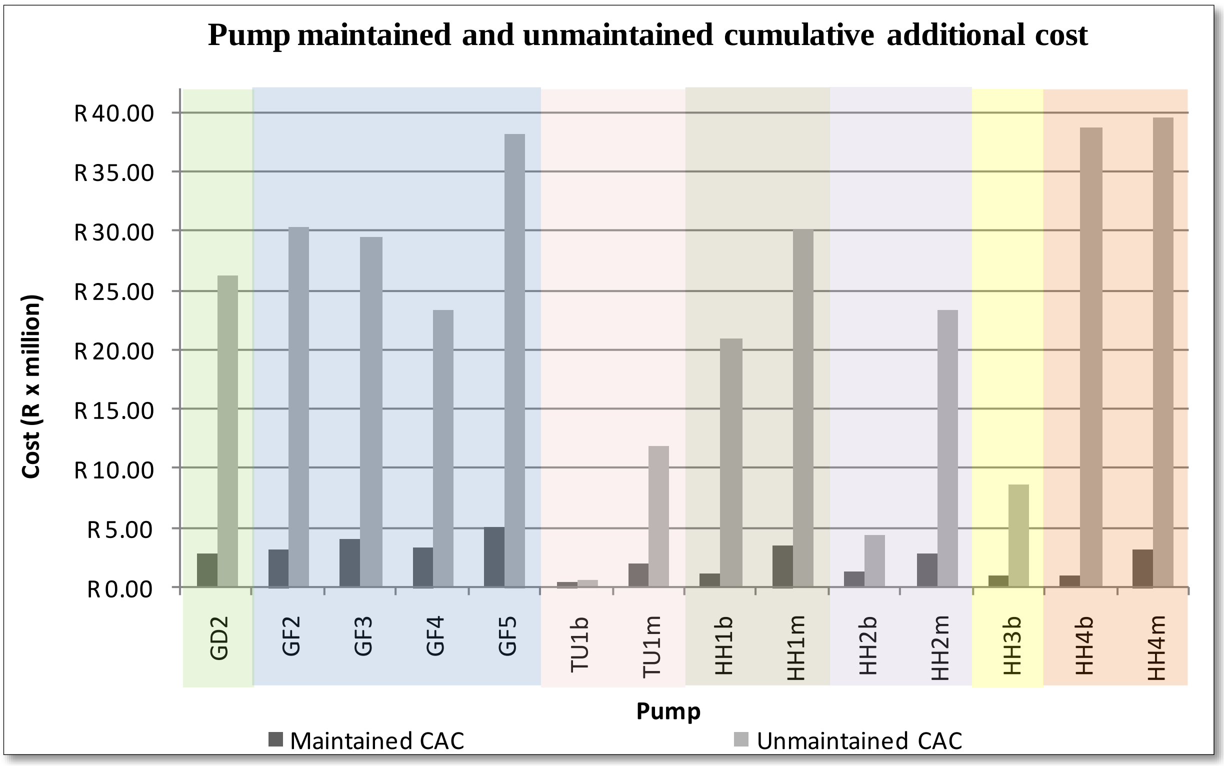


**Figure 48: Maintained and unmaintained cumulative additional cost**

With each pump set, the percentage savings that can be realised were given in the case studies. These savings can only be realised if the correct maintenance procedures are applied at the recommended maintenance period. Figure 48 shows the comparison between the maintained and unmaintained cumulative additional cost that is paid towards energy costs due to the effect of efficiency decay in a pump set. As given in each case, it is clear that the possible savings are immense given that the pump set is maintained and the efficiency of the pump set are kept as close to its original efficiency.

Considering the last two pumps in Figure 48, HH4b and HH4m, the unmaintained CAC is more than displayed in the figure. The values shown there were reached at week 18 of year five and week 24 of year three for pumps HH4b and HH4m respectively. Thus, the given savings at each respective pump are actually more when considering the total period of five years.

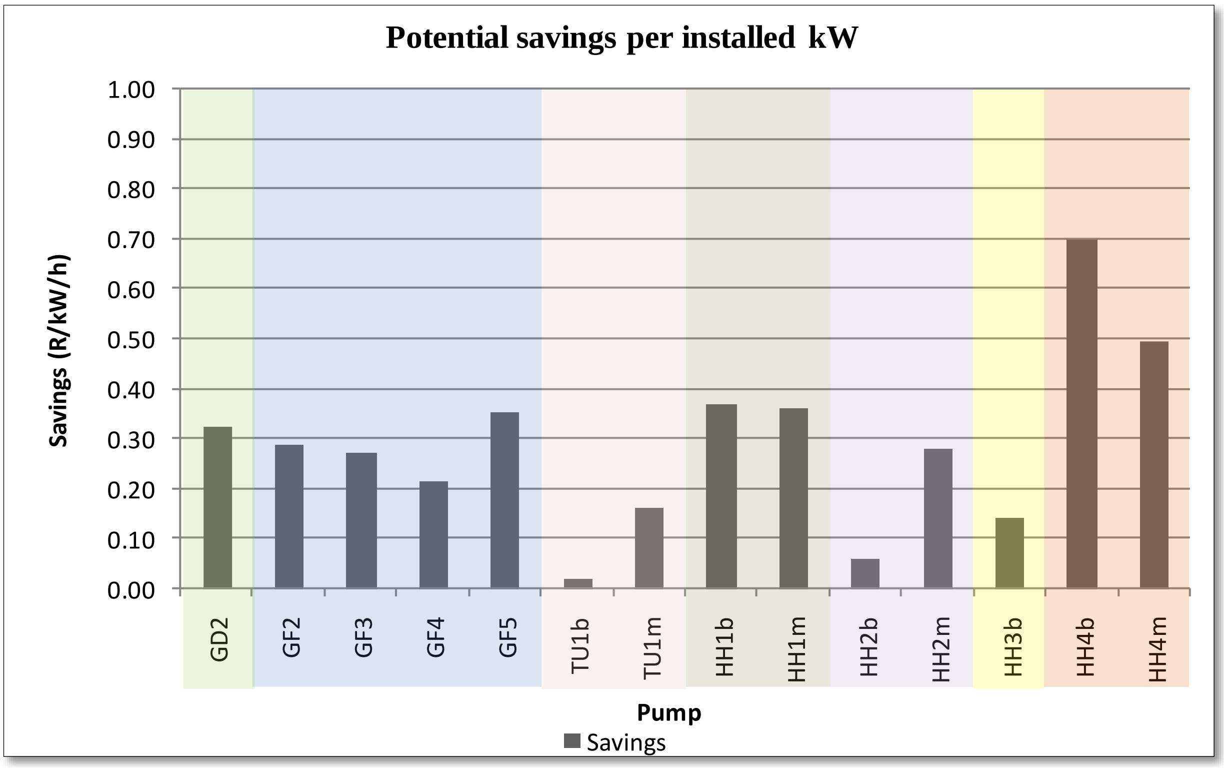


Figure 49: Potential savings per installed kW

In order to quantify the effect of the efficiency decay of a pump set, the potential savings per installed kW was determined over the simulated five years of operation. The results for the possible savings are shown in Figure 49 and given in Rand/kilowatt/hour. It is evident when comparing all the results that there is not a very strong correlation between the different pumps. The rate of efficiency decay varies considerably from pump to pump. Even the same pumps in a single pump station have a wide range in efficiency decay.

However, for the sake of quantifying the effect of a decaying pump set efficiency, according to the results obtained from this study, the average savings that can be realised by doing regular and correct maintenance on pump sets is 0.29 R/kW/h. However, it should be noted that due to the poor quality of the data obtained and the lack of maintenance data from any of the 14 pumps in this study, this potential saving value stated is not an absolute value and cannot be used for further studies.

### Maintenance costs

The aim of the study is to quantify the unnecessary additional operating costs by calculating the efficiency decay of the pumps in bulk water distribution systems as well as to evaluate the accuracy of the available data. This means that only the energy costs due to the decay in efficiency was considered in this study. In order to determine the breakeven point for cost optimal operation, maintenance costs should also be included in the calculation, however, as stated in section 1.5 maintenance costs fall outside the scope of this study.

Mentioned earlier in this dissertation, DWS follow a run-to-fail maintenance structure. For this reason, and due to the complete lack of maintenance data, a very brief study was done to determine the breakeven point. The breakeven point would occur where the possible saving realised exceeds the cost of replacing the entire pump with a new pump. Effectively, the only maintenance costs would be the replacement cost of the pump plus the labour cost for installing the new pump.

When considering bulk water pump stations from DWS it was assumed that the average pump size is 1 MW. A price was obtained from Sulzer South Africa on the most commonly used pump in DWS pump stations, the horizontally split casing centrifugal pump. The price on the pump was approximately R 1 120 000.00. Utilising the potential savings of 0.29 R/kW/h, the conclusion was that the pump could be replaced every 24 weeks of continual operation. However, replacing a pump every 24 weeks seems impractical. It is therefore proposed that a more in depth investigation into the maintenance and replacement costs of similar centrifugal pumps be conducted. This result also

These calculations were performed assuming that there are no additional costs, such as labour, that will have an influence the replacement cost, and consequently, the period at which the pump should be replaced. In addition, price quotes for three pumps were obtained to determine an average pump price (R/kW) and it was found the higher the rated power for a pump become the lower the unit price for the pump becomes. The prices ranged from 3 000 R/kW for a 170 kW pump to 582 R/kW for a 2 750 kW pump. This phenomenon had a drastic influence on the time at which the breakeven point was reached.

It was found that the bigger the pump becomes in the rated power and the less the unit price for the pump becomes, the shorter the period for replacing the pump with a complete new pump becomes. These result further to the conclusion that the result obtained for quantifying the potential savings is not an absolute value and cannot be used for further studies.

## 4.8 Conclusion

A total of fourteen pump sets were analysed. The data and results of each pump set were presented in table format. The data obtained for the first pump set at the respective pump stations were plotted together with the prediction of the efficiency decay. The detailed discussion and graphs for the remaining pump sets are provided in APPENDIX C. A graph for each pump set was plotted showing the unmaintained CAC as well as the MCAC. Also, for each pump set, a graph showing the maintained and unmaintained pump set efficiency was plotted.

The results for the pump set were given in a tabulated format. The table of results showed the maintenance interval for each pump set according to its predicted efficiency decay and the criterion set for maximum allowable decay in efficiency. The table also showed the CAC, should the efficiency of the pump set continuously decay over the simulated period. The table also gives the MCAC, should the pump set undergo maintenance as described in Chapter 2 of this dissertation and the pump set efficiency be reinstated to its initial value at the end of the maintenance period.

Due to the poor quality of the data obtained from each pumps set and the lack of maintenance data from any one of the fourteen pump sets, the results of these studies are for informative purposes only and cannot be used as absolute values for further studies.

# CHAPTER 5

## Conclusion and recommendations

*Chapter 5*

*Chapter 5 concludes this dissertation and discusses recommendations for further studies.*

# 5 CONCLUSION AND RECOMMENDATIONS

## 5.1 Introduction

By analysing the usage of water in South Africa together with the energy consumption from pumps in the industry, especially bulk water distribution systems, a problem was identified that a need exists to determine what influence the decay in efficiency of bulk water pumps has on energy costs.

It was found that 35% of water usage in South Africa is allocated to domestic and urban use, mining, industry and power generation, which is directly supplied by DWS. Furthermore it was seen that of all the water supplied to consumer units, 44.7% of this water is supplied free of charge making the need to supply water as efficiently as possible.

The effect of energy on the LCC of a pump accounts for about 60% of the total cost. The remaining costs are attributed towards maintenance, about 26%, and capital costs, about 14%. These energy costs of a pump can be reduced by maintaining the pump and ensuring that the efficiency of the pump remains as high as possible.

## 5.2 Operation and maintenance of centrifugal pump sets

The basic working of a centrifugal pump was explained followed by factors influencing the efficiency of a centrifugal pump. Two main factors that influence the efficiency of a pump were identified as operational factors and mechanical factors. Detailed descriptions of the factors, both operational and mechanical, were discussed. The same was done with electrical induction motors.

Monitoring is essential in detecting faults and knowing the state of a pump. Different types of monitoring exists and the correct method should be used for the specific application. Various methods of monitoring can be followed. In DWS the most commonly used method of monitoring is SCADA. A detailed explanation of how a SCADA monitoring system works was given. A description of the importance of monitoring systems was discussed.

Failure modes and corrective procedures of both centrifugal pumps and induction motors were discussed. Centrifugal pumps can experience hydraulic and mechanical failures. These failure modes were summarised in table format giving the fault mode, fault symptoms and corresponding corrective procedures. For induction motors, the leading cause of failures are due to bearing failure which accounts for approximately 41% of the failures.

Maintenance is crucial in keeping machinery in good working order and maintaining a high pump system efficiency. Maintenance consists of three main types: breakdown maintenance, CBM and TBM. The most popular maintenance procedure used is CBM whose goal is to find an optimum cost between breakdown maintenance and TBM.

The benefits of maintaining a high pump efficiency can be great. A review on literature was done on cases where savings were realised after analysing a given pump system and performing the necessary changes such as doing regular maintenance or altering the pump system. From the literature, savings from 2% - 37% were realised.

## 5.3 Energy consumption analysis of pump stations

The acquisition of data from various pump stations were described. The data was obtained from manually entered logbooks. Due to the nature of the research done, it was impossible to generate new data within the available time frame.

The method used for calculating the efficiency of each pump set is the conventional method. Certain constraints could exist such as not knowing the flow rate through the specific pump. In certain cases, only one flow meter could be installed at a pump station measuring the total flow rate from the pump station. A method was formulated to calculate the flow rate of the specific pump through Gauss elimination.

After calculating the efficiency of a pump, the efficiency decay was predicted by making use of linear regression. The formulas for predicting the efficiency decay through linear regression were given. Guidelines for interpreting the result of a predicted efficiency decay were tabulated.

The CAC due to the decay of a pump's efficiency was formulated and calculated over a period of five years of continuous operation. The charges included in the calculation were tabulated and the formula for calculating the operational costs were formulated. The PEI was introduced which was used to determine the maintenance interval for a simulated maintained pump. The MCAC was calculated.

## 5.4 Assessment of energy consumption results

A total of fourteen pump sets were obtained and the efficiency decay of each was determined. The results from each pump set were presented where the data obtained was plotted together with the prediction of the efficiency decay from the data obtained. A graph for each pump set was plotted showing the unmaintained CAC as well as the MCAC. Also, for each pump set, a graph showing the maintained and unmaintained pump set efficiency was plotted.

The results for each pump set were given in a tabulated format. The table of results showed the maintenance interval for each pump set according to its predicted efficiency decay and the criterion set for maximum allowable decay in efficiency. The table also showed the CAC should the efficiency of the pump set continuously decay over the simulated period. The table shows the MCAC should the pump set undergo maintenance as described in Chapter 2 and the pump set efficiency be reinstated to its initial value at the end of the maintenance period.

The results of all the pump sets were combined for comparison with each other in the conclusion of Chapter 4. It was concluded that a strong correlation between the individual pumps relating to the rate of efficiency decay does not exist. However, the possible saving for each pump set was calculated and quantified in Rand/kW/h and reflected in Figure 49. An average possible savings per installed kilowatt for the fourteen pump sets was calculated and found to be 0.29 R/kW/h. However, it is important to note that due to the poor quality of the data obtained and the lack of maintenance data, this stated savings value is not an absolute value and cannot be used for further studies.

## 5.5 Conclusion

The goal of this study was to quantify the effect that a decaying pump efficiency has on bulk water distribution systems and to evaluate the accuracy of the available data within the pump stations. It is concluded that allowing a pump set's efficiency to decay without reinstating the efficiency by doing the correct monitoring and regular maintenance, will result in tremendous unnecessary energy costs.

Although this dissertation focused only on bulk water supply systems, the theory in this study is not limited to bulk water systems. The theory is applicable to any other industry or sector that include pumps in their system.

It was also found that data obtained from logbooks, which are manually filled by operators, can be very unreliable. It seemed that certain operators recognise a trend in the data they enter into the book and then, instead of physically taking the correct readings, they continue the pattern without confirming the actual readings.

## 5.6 Recommendations

This study only focused on the pump set efficiency which is a combined efficiency of the pump and the electrical motor. It is recommended that further studies are done where the efficiency of the pump and the electrical motor is monitored separately and the effect of only the pump efficiency decay and the effect of only the electrical motor decay is quantified.

Further work could be done to more accurately predict the efficiency decay of the pump system or the pump alone and the motor alone. This could be done by obtaining more accurate data by making use of monitoring systems as described in this dissertation.

It is recommended that the added additional costs due to the decay of efficiency be compared to the maintenance costs in a financial analysis to determine the breakeven point for cost optimal operation.

This study serves as a motivation to all industrial systems that by implementing correct monitoring and maintenance on the plant, this could save millions in energy costs.

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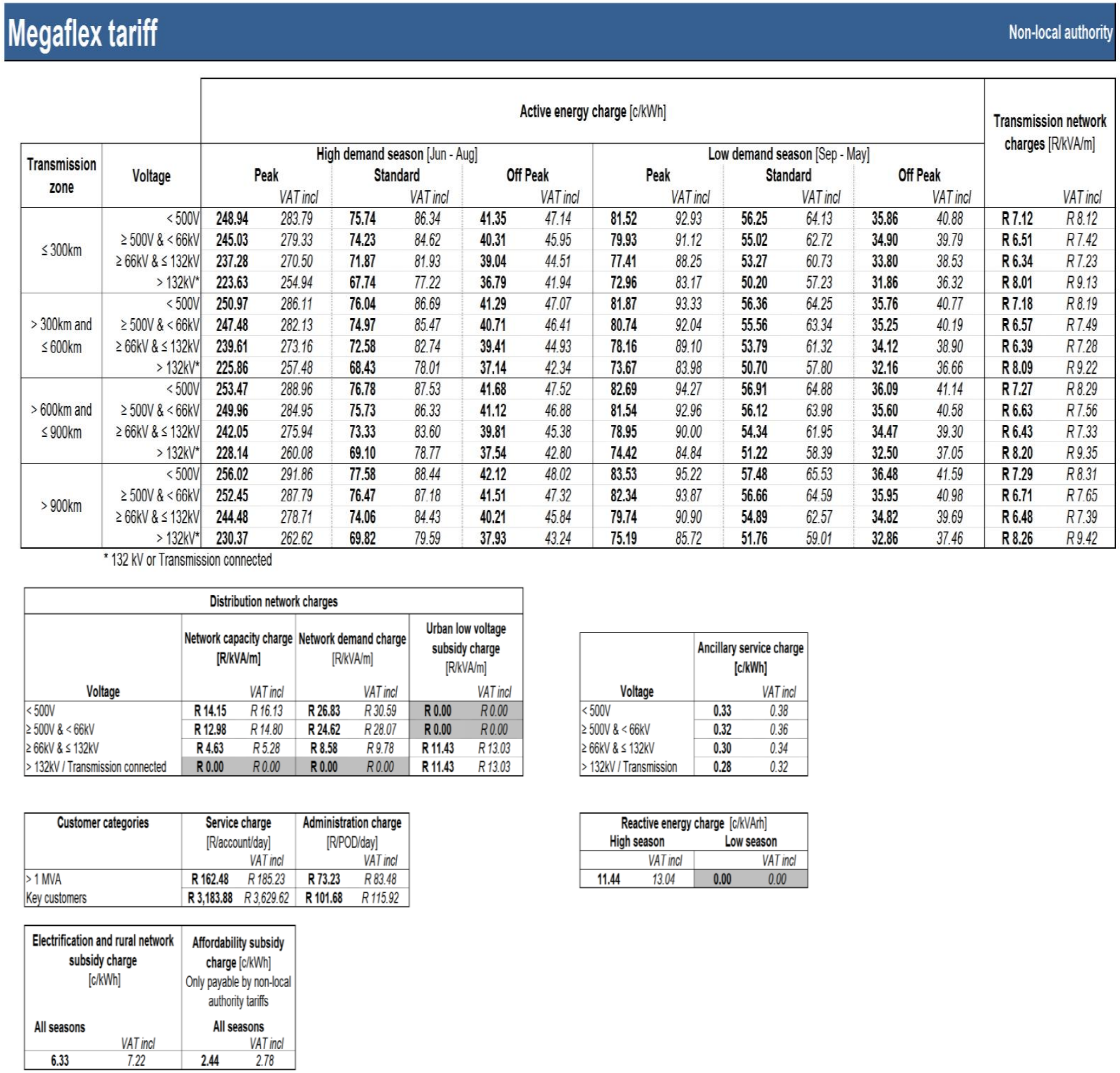
# APPENDIX A - Megaflex tariff structure

Eskom Megaflex tariff structure charges for 2015/2016.



**Megaflex tariff** Non-local authority

| | | Active energy charge [c/kWh] | | | | | | | | | | | | Transmission network charges [R/kVA/m] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | High demand season [Jun - Aug] | | | | | | Low demand season [Sep - May] | | | | | | | |
| Transmission zone | Voltage | Peak | | Standard | | Off Peak | | Peak | | Standard | | Off Peak | | | |
| | | | VAT incl | | VAT incl | | VAT incl | | VAT incl | | VAT incl | | VAT incl | | VAT incl |
| ≤ 300km | < 500V | **248.94** | *283.79* | **75.74** | *86.34* | **41.35** | *47.14* | **81.52** | *92.93* | **56.25** | *64.13* | **35.86** | *40.88* | **R 7.12** | *R 8.12* |
| | ≥ 500V & < 66kV | **245.03** | *279.33* | **74.23** | *84.62* | **40.31** | *45.95* | **79.93** | *91.12* | **55.02** | *62.72* | **34.90** | *39.79* | **R 6.51** | *R 7.42* |
| | ≥ 66kV & ≤ 132kV | **237.28** | *270.50* | **71.87** | *81.93* | **39.04** | *44.51* | **77.41** | *88.25* | **53.27** | *60.73* | **33.80** | *38.53* | **R 6.34** | *R 7.23* |
| | > 132kV* | **223.63** | *254.94* | **67.74** | *77.22* | **36.79** | *41.94* | **72.96** | *83.17* | **50.20** | *57.23* | **31.86** | *36.32* | **R 8.01** | *R 9.13* |
| > 300km and ≤ 600km | < 500V | **250.97** | *286.11* | **76.04** | *86.69* | **41.29** | *47.07* | **81.87** | *93.33* | **56.36** | *64.25* | **35.76** | *40.77* | **R 7.18** | *R 8.19* |
| | ≥ 500V & < 66kV | **247.48** | *282.13* | **74.97** | *85.47* | **40.71** | *46.41* | **80.74** | *92.04* | **55.56** | *63.34* | **35.25** | *40.19* | **R 6.57** | *R 7.49* |
| | ≥ 66kV & ≤ 132kV | **239.61** | *273.16* | **72.58** | *82.74* | **39.41** | *44.93* | **78.16** | *89.10* | **53.79** | *61.32* | **34.12** | *38.90* | **R 6.39** | *R 7.28* |
| | > 132kV* | **225.86** | *257.48* | **68.43** | *78.01* | **37.14** | *42.34* | **73.67** | *83.98* | **50.70** | *57.80* | **32.16** | *36.66* | **R 8.09** | *R 9.22* |
| > 600km and ≤ 900km | < 500V | **253.47** | *288.96* | **76.78** | *87.53* | **41.68** | *47.52* | **82.69** | *94.27* | **56.91** | *64.88* | **36.09** | *41.14* | **R 7.27** | *R 8.29* |
| | ≥ 500V & < 66kV | **249.96** | *284.95* | **75.73** | *86.33* | **41.12** | *46.88* | **81.54** | *92.96* | **56.12** | *63.98* | **35.60** | *40.58* | **R 6.63** | *R 7.56* |
| | ≥ 66kV & ≤ 132kV | **242.05** | *275.94* | **73.33** | *83.60* | **39.81** | *45.38* | **78.95** | *90.00* | **54.34** | *61.95* | **34.47** | *39.30* | **R 6.43** | *R 7.33* |
| | > 132kV* | **228.14** | *260.08* | **69.10** | *78.77* | **37.54** | *42.80* | **74.42** | *84.84* | **51.22** | *58.39* | **32.50** | *37.05* | **R 8.20** | *R 9.35* |
| > 900km | < 500V | **256.02** | *291.86* | **77.58** | *88.44* | **42.12** | *48.02* | **83.53** | *95.22* | **57.48** | *65.53* | **36.48** | *41.59* | **R 7.29** | *R 8.31* |
| | ≥ 500V & < 66kV | **252.45** | *287.79* | **76.47** | *87.18* | **41.51** | *47.32* | **82.34** | *93.87* | **56.66** | *64.59* | **35.95** | *40.98* | **R 6.71** | *R 7.65* |
| | ≥ 66kV & ≤ 132kV | **244.48** | *278.71* | **74.06** | *84.43* | **40.21** | *45.84* | **79.74** | *90.90* | **54.89** | *62.57* | **34.82** | *39.69* | **R 6.48** | *R 7.39* |
| | > 132kV* | **230.37** | *262.62* | **69.82** | *79.59* | **37.93** | *43.24* | **75.19** | *85.72* | **51.76** | *59.01* | **32.86** | *37.46* | **R 8.26** | *R 9.42* |

* 132 kV or Transmission connected

| Distribution network charges | | | | | | |
|---|---|---|---|---|---|---|
| | Network capacity charge [R/kVA/m] | | Network demand charge [R/kVA/m] | | Urban low voltage subsidy charge [R/kVA/m] | |
| Voltage | | VAT incl | | VAT incl | | VAT incl |
| < 500V | **R 14.15** | *R 16.13* | **R 26.83** | *R 30.59* | **R 0.00** | *R 0.00* |
| ≥ 500V & < 66kV | **R 12.98** | *R 14.80* | **R 24.62** | *R 28.07* | **R 0.00** | *R 0.00* |
| ≥ 66kV & ≤ 132kV | **R 4.63** | *R 5.28* | **R 8.58** | *R 9.78* | **R 11.43** | *R 13.03* |
| > 132kV / Transmission connected | **R 0.00** | *R 0.00* | **R 0.00** | *R 0.00* | **R 11.43** | *R 13.03* |

| | Ancillary service charge [c/kWh] | |
|---|---|---|
| Voltage | | VAT incl |
| < 500V | **0.33** | *0.38* |
| ≥ 500V & < 66kV | **0.32** | *0.36* |
| ≥ 66kV & ≤ 132kV | **0.30** | *0.34* |
| > 132kV / Transmission | **0.28** | *0.32* |

| Customer categories | Service charge [R/account/day] | | Administration charge [R/POD/day] | |
|---|---|---|---|---|
| | | VAT incl | | VAT incl |
| > 1 MVA | **R 162.48** | *R 185.23* | **R 73.23** | *R 83.48* |
| Key customers | **R 3,183.88** | *R 3,629.62* | **R 101.68** | *R 115.92* |

| Reactive energy charge [c/kVArh] | | | |
|---|---|---|---|
| High season | | Low season | |
| | VAT incl | | VAT incl |
| **11.44** | *13.04* | **0.00** | *0.00* |

| Electrification and rural network subsidy charge [c/kWh] | | Affordability subsidy charge [c/kWh] Only payable by non-local authority tariffs | |
|---|---|---|---|
| All seasons | | All seasons | |
| | VAT incl | | VAT incl |
| **6.33** | *7.22* | **2.44** | *2.78* |

## APPENDIX B - Flow calculation derived method

In this appendix, the method derived to calculate the flow rate of each individual pump line in a pump station with parallel pumps where only one common flow meter measuring the total flow from the pump station is presented.

The most commonly used flow meters within DWS pump stations are ultrasonic flow meters. At numerous DWS pump stations only one flow meter is installed per pump station. These flow meters are installed just outside the pump station in a separate chamber measuring the combined flow rate of the operating pumps. This presents a problem. In order to calculate the efficiency of a specific pump set, the flow rate of this single pump set is needed. In the following equations a method is formulated that will assist in calculating the flow rate of each individual pump set.

The law of conservation of energy is used to calculate the flow rate of each individual pump set. The law of conservation of energy states that energy cannot be created nor can it be destroyed. Energy can only be transformed into different forms of energy being it sound, heat, momentum etc. The energy in the system presented by the pump stations are pressure energy and kinetic energy.

**Equation 14**

$$\frac{P_i}{\rho g} + \frac{V_i^2}{2g} + Z_i = \frac{P_o}{\rho g} + \frac{V_o^2}{2g} + Z_o + h_l \text{ [23]}$$

With:

P - pressure
ρ - fluid density
g - gravitational acceleration 9.81 m/s$^2$
V - flow velocity
Z - elevation
$h_l$ - total head loss due to friction and minor losses between the points
i, o - in, out respectively

Equation 14 is most commonly known as the Bernoulli Equation. It states that the total energy (internal energy, kinetic energy and potential energy respectively) entering the system equals the total energy leaving the system plus a loss term that accounts for the energy losses between the points due to friction and minor losses. [23]

The Bernoulli Equation can also be used where multiple points exist. The sum of the energy entering the system boundary should equal the sum of the energy leaving the system boundary. This theory is given in Equation 15 and shown in Figure 50.

**Equation 15**

$$\sum_{i=1}^{m} E_i = \sum_{o=1}^{n} E_o + h_l$$

With:

$E_i$ - total energy entering the system boundary

$E_o$ - total energy leaving the system boundary

$h_l$ - total head loss due to friction and minor losses between the points

m - number of energy entering points

n - number of energy leaving points

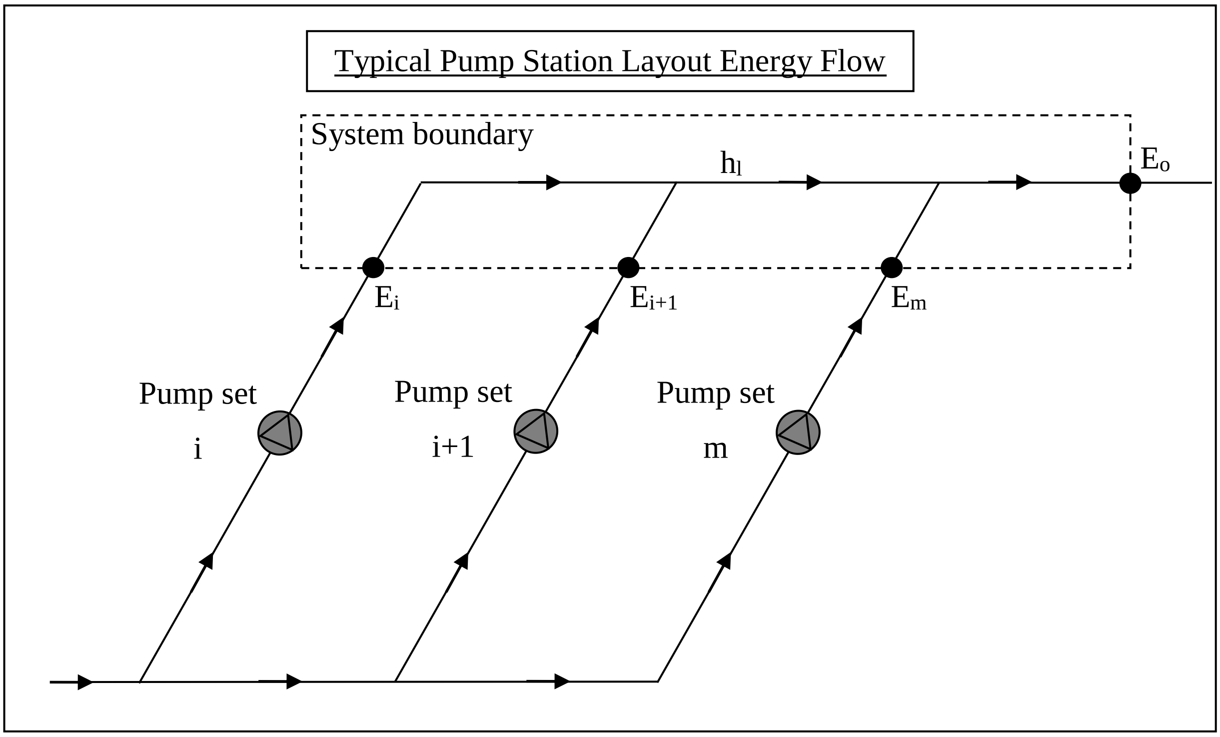


Figure 50: Typical pump station layout energy flow

Due to the nature of the pump stations considered, the number of energy outlets from the system will always equal one. The number of energy inlets to the system will always be equal to the number of pump sets in the pump station. From the aforementioned facts, Equation 15 can be simplified and written in the format of Equation 16. The new energy flow through the system is shown in Figure 51.

In the case where only one flow meter is installed at a pump station measuring the total flow from the pump station, the physical positions of the of the energy inlet points to the system boundary are at the pressure sensors directly after the pumps. The physical position of the energy outlet point from the system boundary is at the position where the flow meter of the pump station is installed.

**Equation 16**

$$\sum_{i=1}^{m} E_i = E_t + h_l$$

With:

$E_i$ - total energy entering the system boundary
$E_t$ - total energy leaving the system boundary
$h_l$ - total head loss due to friction and minor losses between the points
m - number of energy entering points

The system boundary in Figure 50 and Figure 51 of a typical pump station layout encloses the delivery manifold of a pump station. The physical layout of the pump station's delivery manifold are all geometrically similar and on the same elevation. This concludes that the elevations of all the energy inlet points to and all the energy outlet points from the system boundary are equal. Considering Equation 14 this states that:

**Equation 17**

$$Z_i = Z_{i+1} = Z_m = Z_o = Z_{o+1} = Z_n = Z_t$$

With:

Z - elevation
i, o - in, out respectively
m - number of energy entering points

n - number of energy leaving points

Due to the statement made above it can be concluded that all the potential energy terms in Equation 14 will be cancelled out.

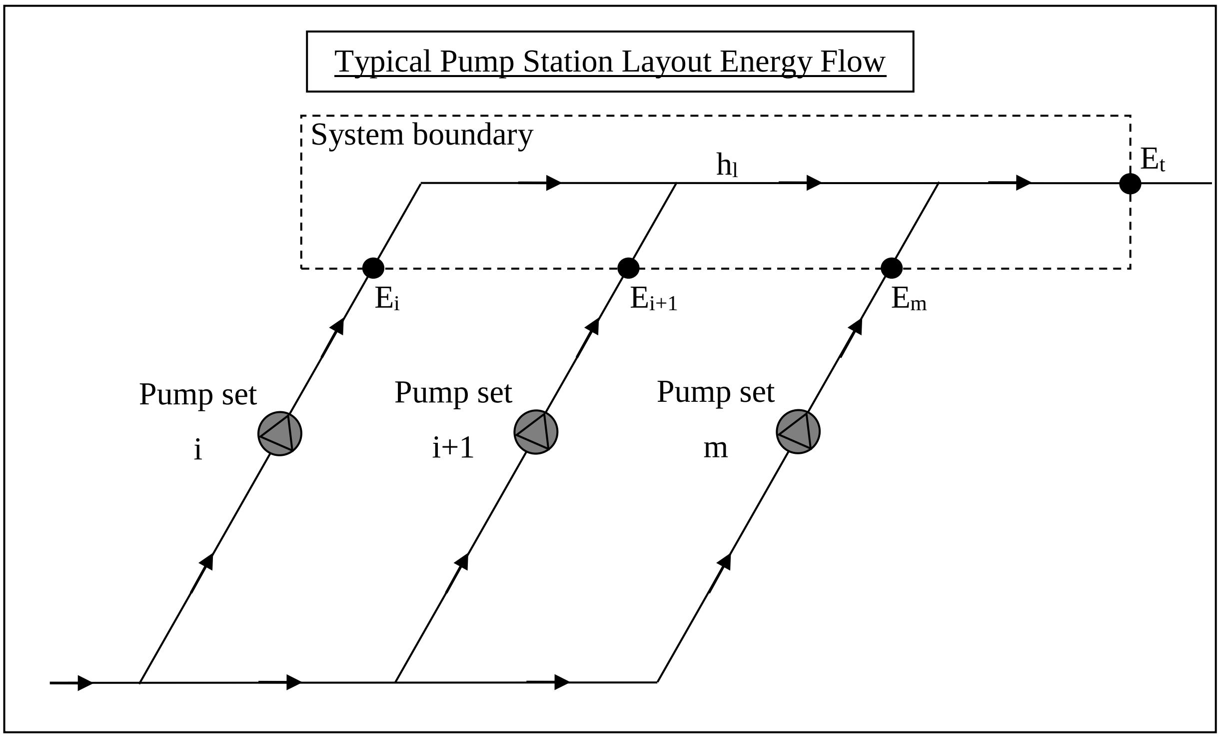


**Figure 51: Actual energy flow through a typical pump station layout**

The loss term in the Bernoulli Equation, $h_l$, is made up from two factors, minor losses and friction losses.

**Equation 18**

$$h_l = \sum h_m + h_f \text{ [23]}$$

With:

$h_l$ - total head loss due to friction and minor losses between the points

$h_m$ - total head loss due to minor losses between the points

$h_f$ - total head loss due to friction losses between the points

The minor losses are calculated in Equation 19 and due to:

- Pipe entrance or exit;
- Sudden expansion or contraction;
- Bends, elbows, tees, and other fittings;
- Valves, open or partially closed or;
- Gradual expansions or contractions.

The magnitude of the minor losses within the system boundary may not be negligibly small; for example, a partially closed valve will have a greater loss than a fully open valve of the same type or even a long section of pipe [63]. On the other hand, the friction losses within the system boundary are negligibly small. This is due to the very short pipe distances that are in the order of several metres.

**Equation 19**

$$\sum h_m = \sum K \frac{V^2}{2g} \text{ [23]}$$

With:

$h_m$ - total head loss due to minor losses between the points

K - minor loss coefficient

V - flow velocity

g - gravitational acceleration 9.81 m/s$^2$

The minor loss coefficient, K, is available from various literature for the different types of losses. [23][63]. Due to the friction losses within the system boundary being negligibly small ($h_f \approx 0$), Equation 18 can be rewritten as follows:

**Equation 20**

$$h_l = \sum h_m = \sum K \frac{V^2}{2g}$$

With:

$h_l$ - total head loss due to friction and minor losses between the points

$h_m$ - total head loss due to minor losses between the points

K - minor loss coefficient

V - flow velocity

g - gravitational acceleration 9.81 m/s$^2$

Consider Equation 17 and Equation 20 and integrate them into Equation 16 and rewrite it into the Bernoulli Equation format. This leads to the energy equation for the system.

**Equation 21**

$$\sum_{i=1}^{m}\left[\frac{P_i}{\rho g}+\frac{V_i^2}{2g}\right]=\frac{P_t}{\rho g}+\frac{V_t^2}{2g}+\sum K\frac{V^2}{2g}$$

With:

P - pressure
$\rho$ - fluid density
g - gravitational acceleration 9.81 m/s$^2$
V - flow velocity
K - minor loss coefficient
i, o - in, out respectively

Equation 21 is the final form of the energy equation that is used to determine the flow rate through each individual pump set. Using Equation 21 to calculate the flow rate through each individual pump set is not as simple. The known variables in the equation are the pressures at the inlet points of the system boundary and the velocity at the outlet of the system boundary. The unknown variables in the equation are the pressure at the outlet of the system boundary and the velocities at the inlet of the system boundary.

For each pump station there will be m+1 unknown variables, m being the number of pump sets in the pump station and the +1 is for the pressure at the outlet of system boundary. To solve for the unknown velocities and the unknown pressure, m+1 different equations will be needed. The method of Gauss elimination is then used to solve for the unknown variables [67].

# APPENDIX C - Remaining pump sets discussion and data

## Tutuka main and booster pumps number 3 and 4

Figure 52 shows the data collected for the booster and main pump number 3 respectively. The data indicates a continuous increase in efficiency of the respective pumps. The quality of the data is poor as indicated by a R-squared value of 0.596 and 0.578 respectively. Also seen in the figure is the efficiency that increase to a value greater than 100% which is impossible. The reason for this poor set of data is unknown.

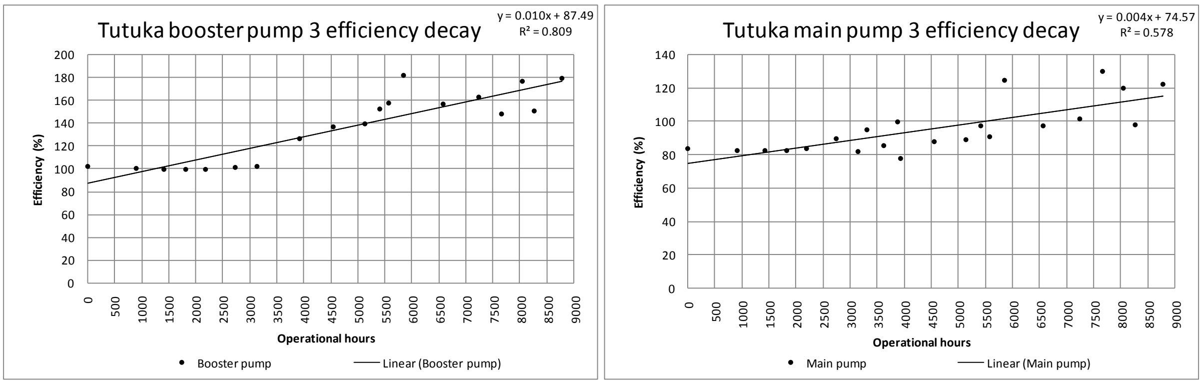


**Figure 52: Tutuka booster and main pump 3 data collected**

Figure 53 shows the data collected for the booster and main pump number 4 respectively. The data obtained is scattered over a wide range of efficiency which results in a very poor R-squared value rendering the data useless as no decay in efficiency can be determined. The time range over which the data could be collected is also insufficiently short. For this reason pump line number 4 could not be included in this study. The reason for this poor set of data is unknown.

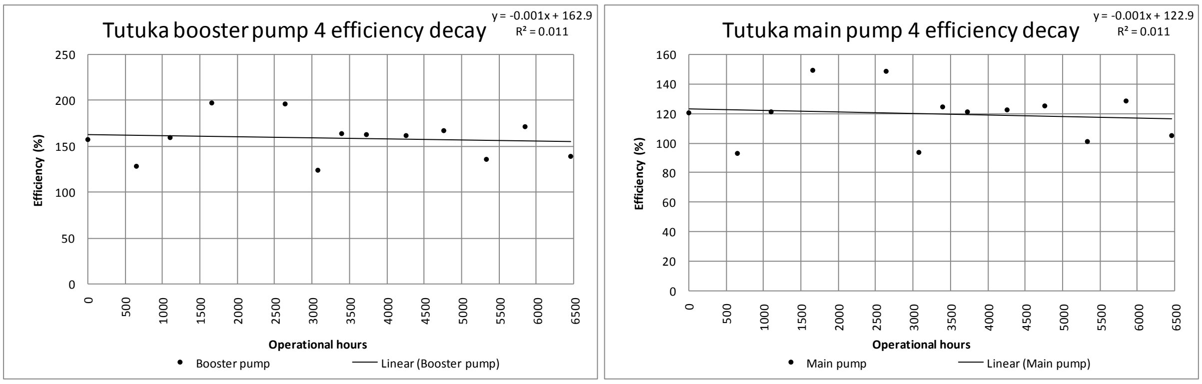


**Figure 53: Tutuka booster and main pump 4 data collected**

## Grootfontein pump number 3

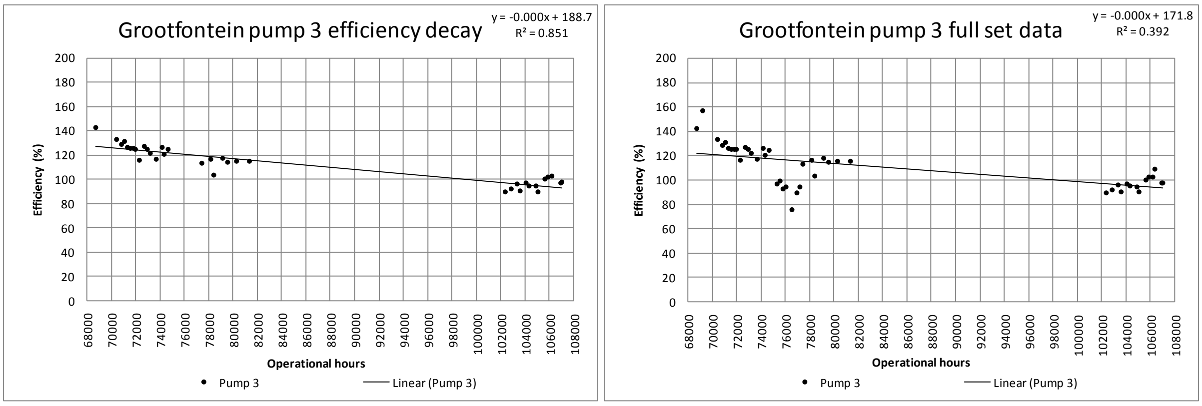


**Figure 54: Grootfontein pump 3 data collected**

The data for Grootfontein pump number 3 is shown in Figure 54. As with Grootfontein pump number 2, the efficiency calculated from the data exceeds 100%. Also a gap in available data exist between 82000 and 102000 hours although the decay in efficiency continues to exist. Again a couple of data points were deleted to obtain an acceptable R-squared value.

**Table 23: Grootfontein pump no. 3 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 2150 | 38270 | 0.851 | 88.77 | 8.931 |

Figure 55 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump.

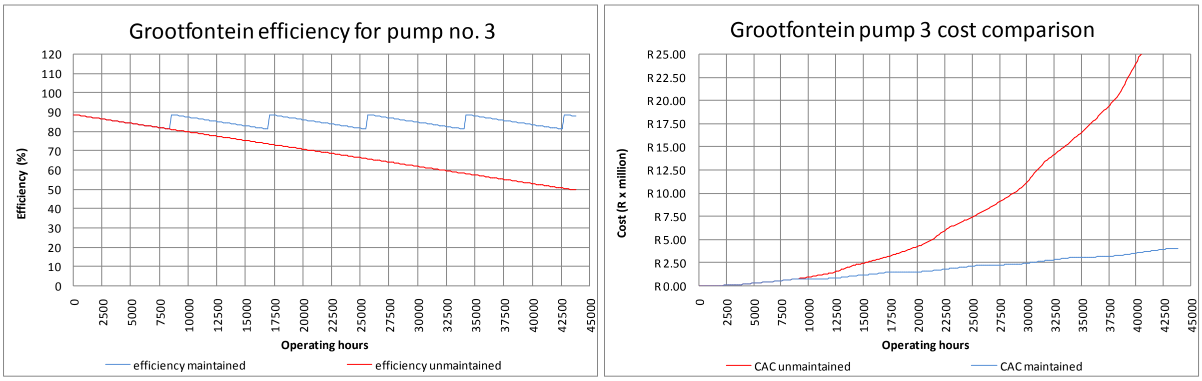


**Figure 55: Grootfontein pump no. 3 efficiency and energy cost comparison**

**Table 24: Grootfontein pump no. 3 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3072 | 8568 | 29 551 945 | 3 995 429 | 86.48 |

Seen in Table 24, possible saving of 86.48% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation.

### Grootfontein pump number 4

The data for Grootfontein pump number 4 is shown in Figure 56. Seen in the original data, before removal of deviating data points, a decay in the efficiency exists up to before 97000 hours after which the efficiency of the pump set has increased. The cause for the increase in the efficiency could not be obtained and could have been due to maintenance done on the pump set. The data points up until before 97000 hours were used to determine the efficiency decay of the pump set.

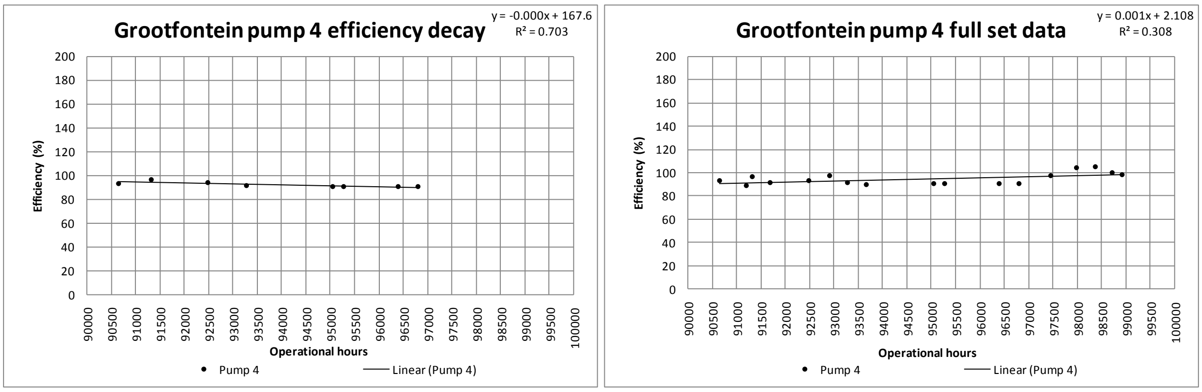


Figure 56: Grootfontein pump 4 data collected

**Table 25: Grootfontein pump no. 4 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 2150 | 8273 | 0.703 | 88.77 | 8.040 |

Figure 57 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump.

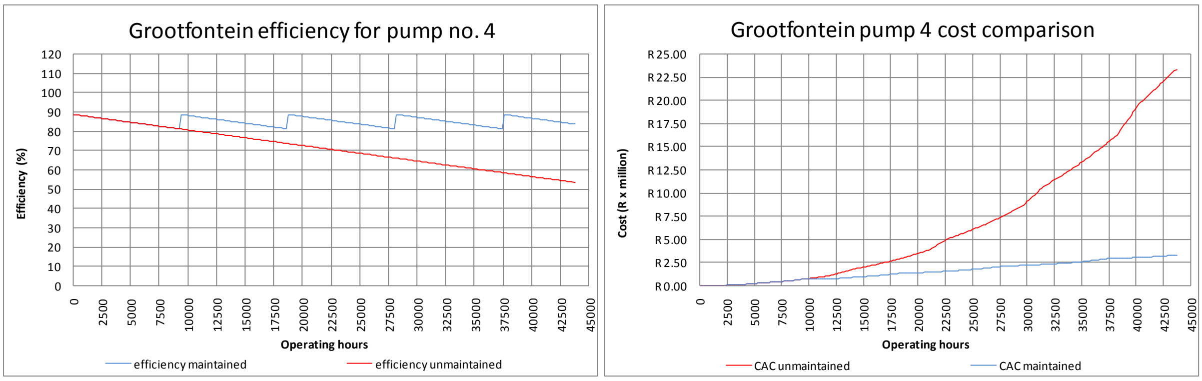


Figure 57: Grootfontein pump no. 4 efficiency and energy cost comparison

**Table 26: Grootfontein pump no. 4 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3072 | 9408 | 23 379 974 | 3 301 324 | 85.88 |

Seen in Table 26, possible saving of 85.88% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation.

## Grootfontein pump number 5

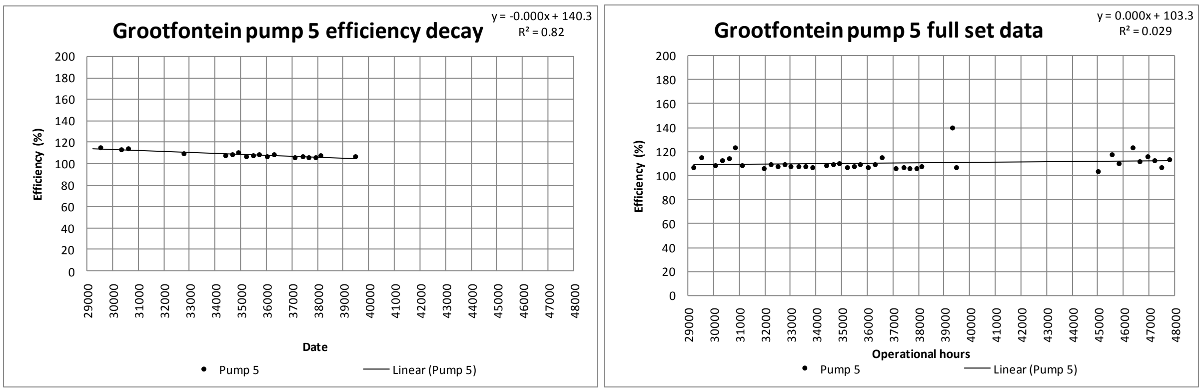


Figure 58: Grootfontein pump 5 data collected

The data for Grootfontein pump number 5 is shown in Figure 58. As in previous pump sets, a period exists where no data were available. For this pump set this period is between 40000 and 45000 hours. The efficiency of the pump set increased from the one period to the next. The reason for the increase is not known but it can be assumed that maintenance has been done on the pump set to increase the efficiency. The range of data used shows a clear decay in efficiency from 29000 to 40000 hours.

As with the previous pump set, the efficiency for this pump set according to the data collected is also greater than 100%. Although, a clear efficiency decay is visible between 29000 and 40000 hours. This efficiency decay together with the initial pump efficiency was used in this case.

**Table 27: Grootfontein pump no. 5 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 2150 | 18600 | 0.82 | 88.77 | 9.027 |

Figure 59 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump.

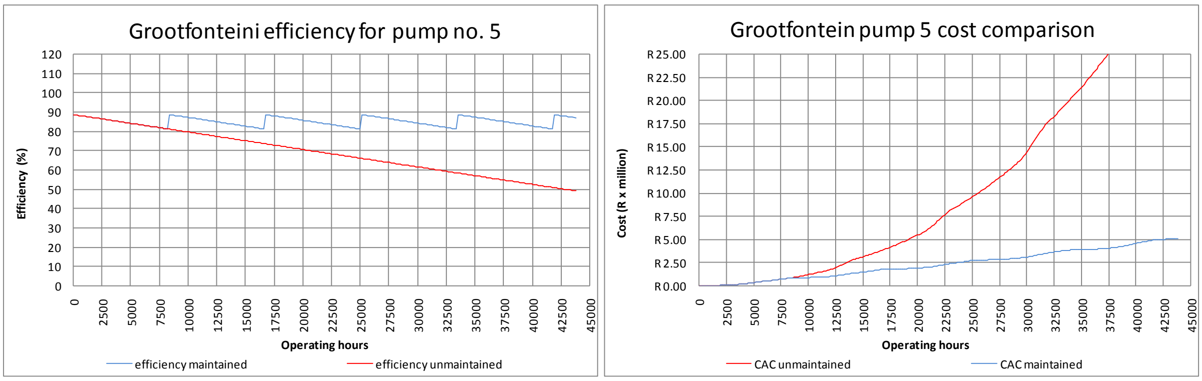


Figure 59: Grootfontein pump no. 5 efficiency and energy cost comparison

**Table 28: Grootfontein pump no. 5 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3072 | 8400 | 38 255 096 | 5 056 436 | 86.78 |

As seen in Table 28, possible saving of 86.78% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation.

## Heyshope main pump number 1

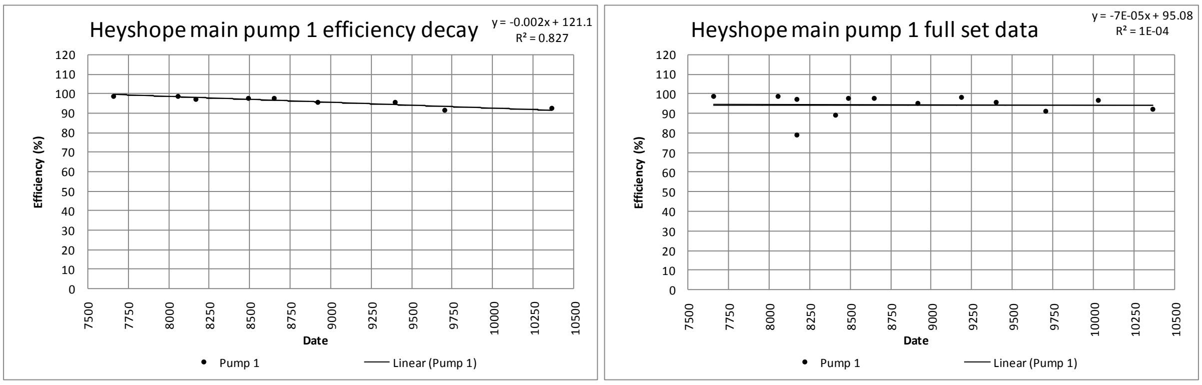


Figure 60: Heyshope main pump 1 data collected

The data for Heyshope main pump number 1 is shown in Figure 60. Some outliers have been deleted to obtain a good R-squared value of 0.827. The range of data used shows a clear decay in efficiency.

**Table 29: Heyshope main pump no. 1 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1683 | 2700 | 0.827 | 90.49 | 28.361 |

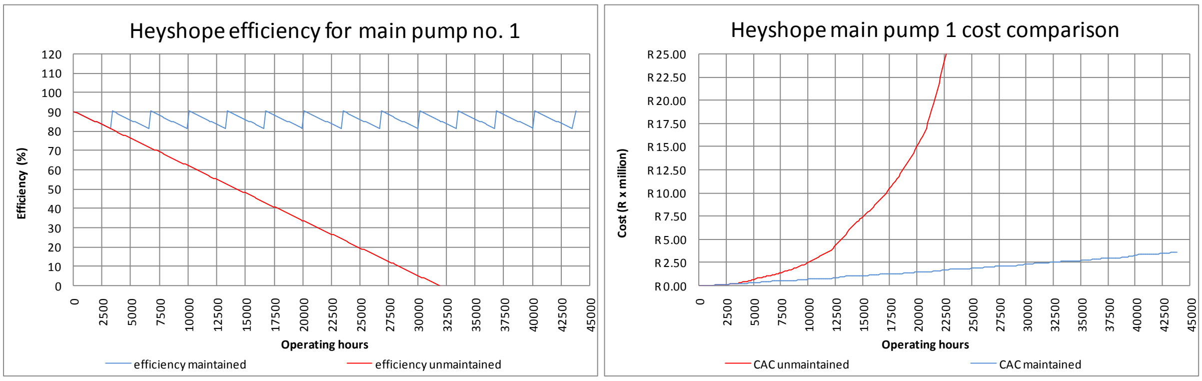


**Figure 61: Heyshope main pump no. 1 efficiency and energy cost comparison**

Figure 61 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump. As seen in the graph displaying the efficiencies, this pump set has a very aggressive efficiency decay, such that after a continual decay the efficiency of the pump set reaches zero after 31717 hours. This is unrealistic as the pump will not continue to decay to a zero efficiency, instead it will fail long before this point is reached. However, the rate of efficiency decay was still used for this study.

**Table 30: Heyshope main pump no. 1 savings**

| Initial PEI (kW/$Mm^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3024 | 3360 | 30 149 423 | 3 616 449 | 88.00 |

Seen in Table 30, possible saving of 88.00% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation. The CAC value is reached within the same duration as it takes the efficiency to reach 0% which is shorter than the complete period under investigation of five years.

## Heyshope booster pump number 2

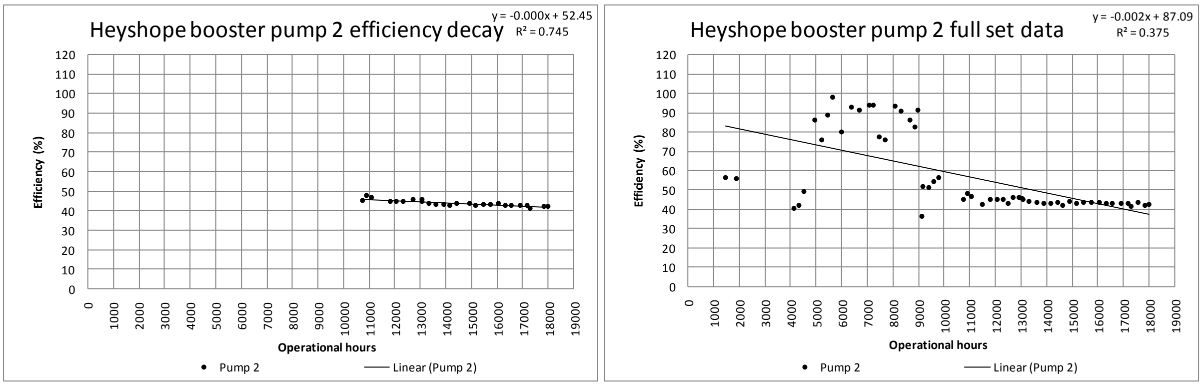


Figure 62: Heyshope booster pump 2 data collected

The data for Heyshope booster pump number 2 is shown in Figure 62. As seen in the original set of data on the right hand side, there is a period from 5000 to 10000 hours where the data points are much higher than the rest of the data and very scattered. The reason for this unusual set of data is unknown but can be attributed to faulty sensors. The same phenomenon will be seen in the main pump 2 following this pump in the same pump line. From 10000 hours onwards the data follows a very good trend. This data was only used to determine the efficiency decay of the pump set as shown on the left hand side.

**Table 31: Heyshope booster pump no. 2 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1232 | 16570 | 0.745 | 90.3 | 5.845 |

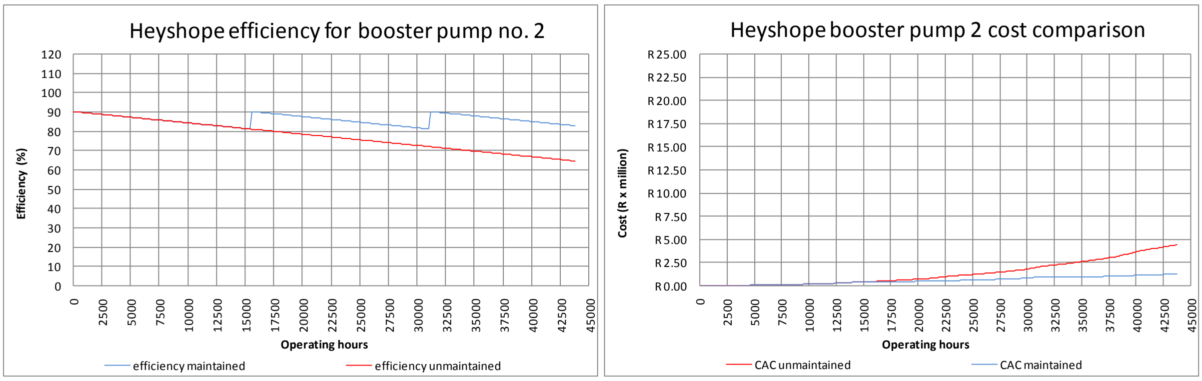


Figure 63: Heyshope booster pump no. 2 efficiency and energy cost comparison

**Table 32: Heyshope booster pump no. 2 savings**

| Initial PEI ($kW/Mm^3/m$) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3018 | 15624 | 4 415 579 | 1 255 069 | 71.58 |

Seen in Table 32, possible saving of 71.58% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation.

## Heyshope main pump number 2

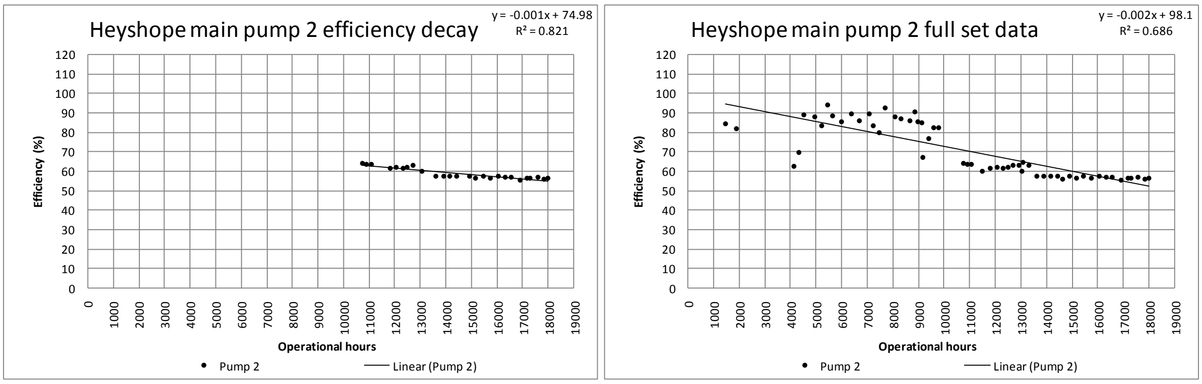


Figure 64: Heyshope main pump 2 data collected

The data for Heyshope main pump number 2 is shown in Figure 64. As with booster pump 2, it is at the same period that the data deviates from the rest of the data and are very scattered. The reason for this unusual set of data is unknown but can be attributed to faulty sensors. From 10000 hours onwards the data follows a very good trend. This data only was used to determine the efficiency decay of the pump set as shown on the left hand side.

**Table 33: Heyshope main pump no. 2 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1683 | 15624 | 0.821 | 90.49 | 11.125 |

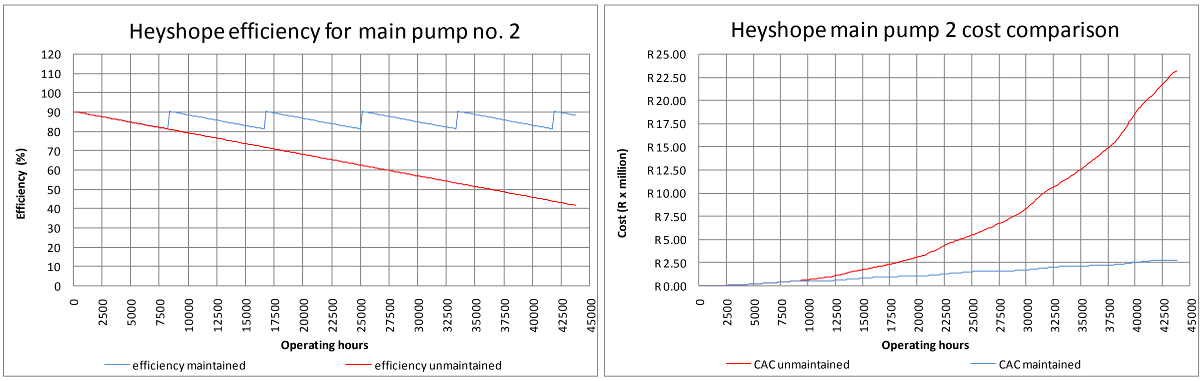


Figure 65: Heyshope main pump no. 2 efficiency and energy cost comparison

Table 34: Heyshope main pump no. 2 savings

| Initial PEI ($kW/Mm^3/m$) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3015 | 8400 | 23 270 199 | 2 784 919 | 88.03 |

Seen in Table 34, possible saving of 88.03% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation.

## Heyshope booster pump number 3

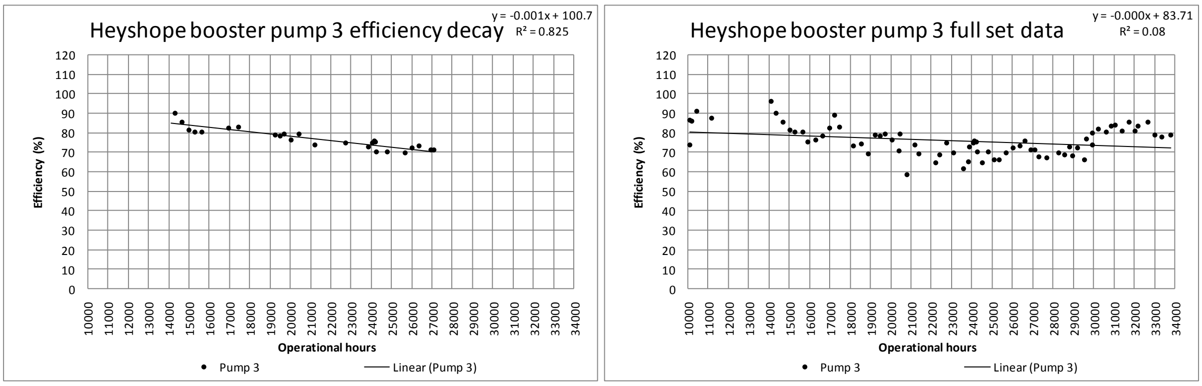


Figure 66: Heyshope booster pump 3 data collected

The data for Heyshope booster pump number 3 is shown in Figure 66. As seen in the original set of data on the right hand side, the data is very scattered. It also seems to follow a wavy pattern from 14000 hours onward. Although, there seem to be a decline in efficiency between 14000 and 29000 hours. A number of outliers had to be deleted to obtain a good R-squared value. Although this set of data is very unreliable, the results for the efficiency decay were still used in this case.

**Table 35: Heyshope booster pump no. 3 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1232 | 23760 | 0.825 | 90.3 | 11.2 |

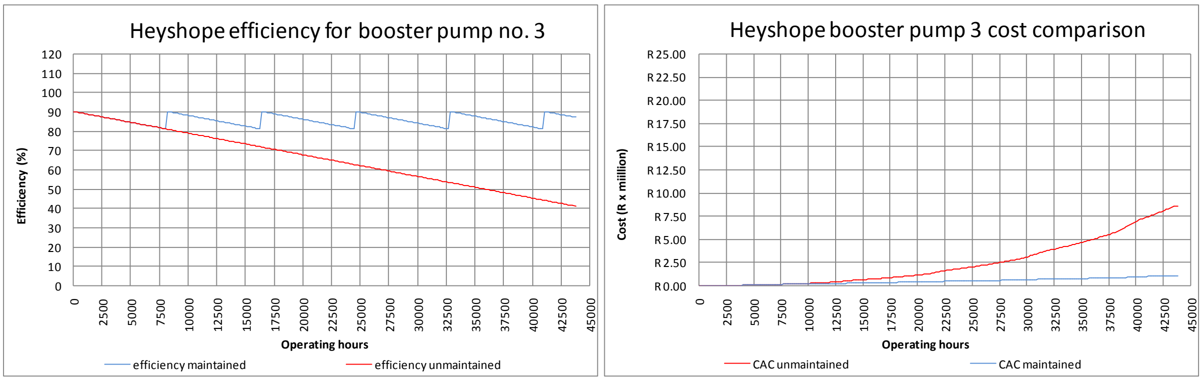


Figure 67: Heyshope booster pump no. 3 efficiency and energy cost comparison

**Table 36: Heyshope booster pump no. 3 savings**

| Initial PEI (kW/$Mm^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3021 | 8232 | 8 621 915 | 1 011 071 | 88.27 |

Seen in Table 36, possible saving of 88.27% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation.

### Heyshope booster pump number 4

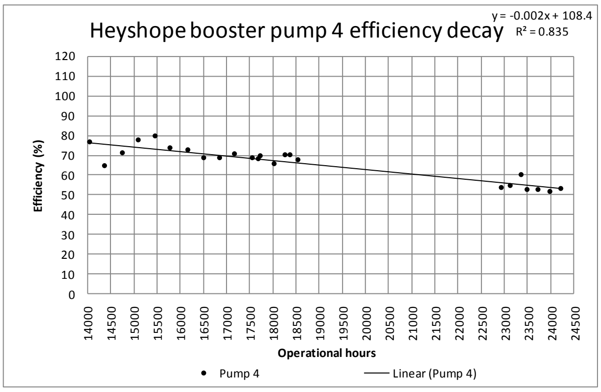


**Figure 68: Heyshope booster pump 4 data collected**

The data for Heyshope booster pump number 4 is shown in Figure 68. A gap in available data exist between 19000 and 23000 hours although the decay in efficiency continues to exist. The full set of data was used as they delivered a very good R-squared value. No outliers were deleted.

**Table 37: Heyshope booster pump no. 4 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1232 | 10171 | 0.835 | 90.3 | 22.766 |

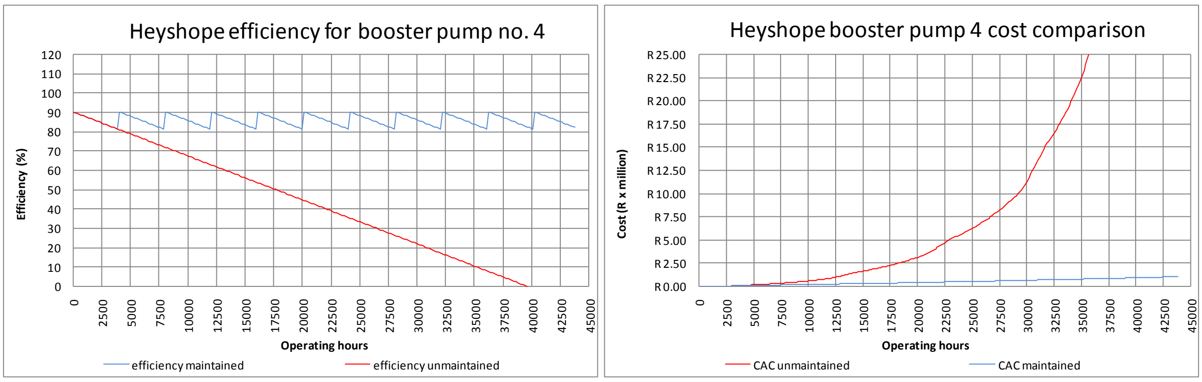


**Figure 69: Heyshope booster pump no. 4 efficiency and energy cost comparison**

Figure 69 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump. As seen in the graph displaying the efficiencies, this pump set has a very aggressive efficiency decay, such that after a continual decay the efficiency of the pump set reaches zero after 39605 hours. This is unrealistic as the pump will not continue to decay to a zero efficiency, instead it will fail long before this point is reached. However, the rate of efficiency decay was still used for this study.

**Table 38: Heyshope booster pump no. 4 savings**

| Initial PEI (kW/Mm$^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3028 | 4032 | 154 238 238 | 1 035 305 | 97.32 |

Seen in Table 38, possible saving of 97.32% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation. The CAC value is reached within the same duration as it takes the efficiency to reach 0% which is shorter than the complete period under investigation of five years.

### Heyshope main pump number 4

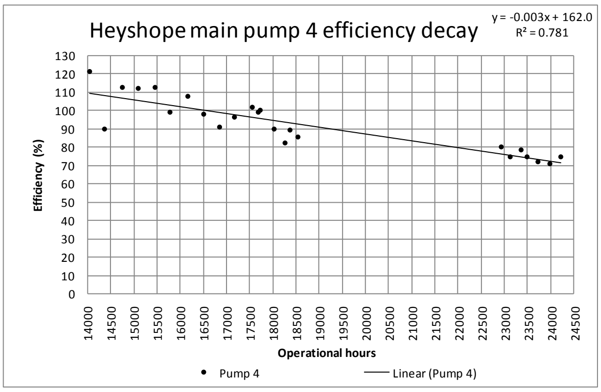


**Figure 70: Heyshope main pump 4 data collected**

The data for Heyshope main pump number 4 is shown in Figure 70. As with previous pump sets, the efficiency calculated from the data exceeds 100%. Similarly, a gap in available data exist between 19000 and 23000 hours although the decay in efficiency continues to exist. The full set of data was used as they delivered a very good R-squared value. No outliers were deleted.

**Table 39: Heyshope main pump no. 4 data**

| Installed capacity (kW per motor) | Data total hours | R-squared value | Pump initial manufactured efficiency (%) | Efficiency decay (%/hour x $10^4$) |
|---|---|---|---|---|
| 1683 | 10171 | 0.781 | 90.49 | 37.347 |

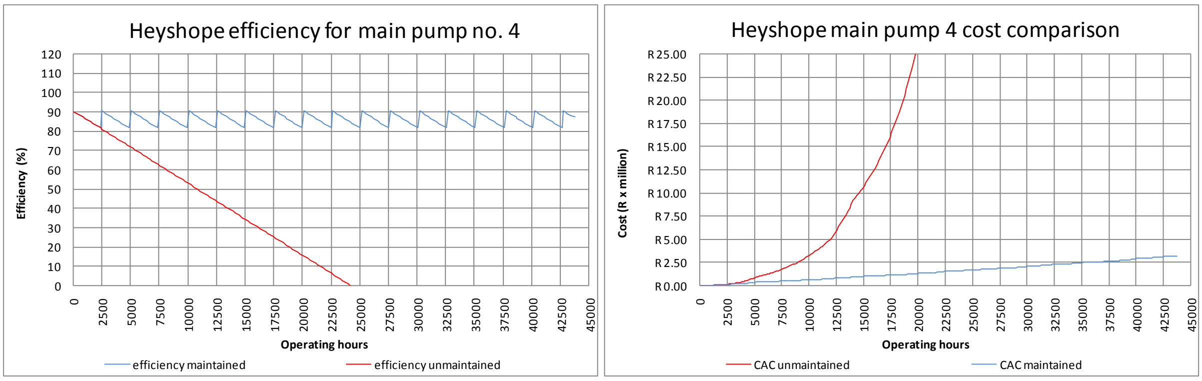


**Figure 71: Heyshope main pump no. 4 efficiency and energy cost comparison**

Figure 71 shows the comparison of the efficiency and energy costs for an unmaintained and maintained pump. As seen in the graph displaying the efficiencies, it can be noted that this pump set has a very aggressive efficiency decay, such that after a continual decay the efficiency of the pump set reaches zero after 24166 hours. This is unrealistic as the pump will not continue to decay to a zero efficiency, instead it will fail long before this point is reached. However, the rate of efficiency decay was still used for this study.

**Table 40: Heyshope main pump no. 4 savings**

| Initial PEI (kW/$Mm^3$/m) | Maintenance Interval (hours) | CAC (R) | MCAC (R) | Savings (%) |
|---|---|---|---|---|
| 3029 | 2520 | 161 817 181 | 3 163 068 | 92.02 |

Seen in Table 40, possible saving of 92.02% could be realised from this pump set given that the correct maintenance procedures are followed as described in Chapter 2 of this dissertation. The CAC value is reached within the same duration as it takes the efficiency to reach 0%which is shorter than the complete period under investigation of five years.