



Improved management of power factors on deep-level mines through monitoring and reporting

R Matthee

 **[orcid.org/ 0000-0003-1055-8457](https://orcid.org/0000-0003-1055-8457)**

Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

Supervisor: Dr JF van Rensburg

Graduation: August 2024

ABSTRACT

Title: Improved management of power factors on deep-level mines through monitoring and reporting

Author: R. Matthee

Supervisor: Dr J.F. van Rensburg

School: North-West University, School for Mechanical Engineering

Degree: Master of Engineering (Mechanical)

Keywords: Power factor management, deep-level mines, energy charges, monitoring, reporting, notifications

In the last few decades, the South African gold mining industry has been confronted with a decline in mining exploration, reduced productivity, and increased operational costs. The industry is highly dependent on electricity and is one of the main energy consumers in South Africa. Subsequently, the ever-increasing price of electricity has become a major contributor to the escalating operational costs.

In recent years, Eskom, South Africa's electricity supplier, has struggled to adequately meet the country's electricity demands. During the peak and standard demand periods of June, July and August, reactive energy charges are used to penalise users with power factors of 0.96 and less. Excess reactive energy increases the total energy demand of a facility and places additional strain on the electrical grid. The reduction in excess reactive energy consumption is vital for the stability of the grid, as this reduces the need for Eskom to resort to load curtailment to reduce the demand which impacts the productivity of electricity-intensive industries such as gold mining.

The management of power factors on deep-level gold mines has become increasingly important to mitigate penalties in the wake of inflated electricity prices and grid instabilities. Unfortunately, most mines lack the required tools to effectively monitor and identify poor power factors until it is made evident in the monthly Eskom bill. Therefore, there is a need to improve the identification of poor power factors and the management thereof.

This study aims to improve the management of power factors on deep-level gold mines by integrating monitoring and reporting tools to platforms already implemented on the mine, enabling the identification of savings opportunities to reduce penalties and network demand charges through power factor performance.

To accomplish this, the waterfall methodology is implemented on the system development life cycle (SDLC) process model to guide the development of the power factor monitoring and reporting tools. These tools comprise a daily performance report, real-time web-based monitoring and data analysis, and notifications via smartphone application integration. The requirements of the tools are established through the shortcomings in the current power factor management approach and will direct the solution implementation. Consumer data is collected and analysed to gather insights into the current state of the power factors and is used for the development of the tools. A case study is used to verify and validate the tools by means of comparative analysis to consumer data and the resulting benefit after implementation.

The power factor management tools were implemented on various mining operations in South Africa. The tools were incorporated and made accessible on platforms already implemented on the mines to avoid any additional implementation costs. All relevant personnel were given access to these tools with the necessary notification protocols in place. Penalties on reactive energy usage equating to R3.36 million were identified along with R3.09 million in excess network demand charges through the performance analysis of the case study deep-level mine operations for the 2020/2021 financial year.

The analysis of the historic data paired with the reporting and monitoring tools allowed for the prioritisation of underperforming operation points of distribution (PODs). The power factor warning notifications facilitated swift investigation into sudden reductions in power factor performance. This contributed to a R3.4 million reduction (year-on-year normalised) in reactive energy charges and excess network demand charges due to reduced capacitor bank downtime. The study objectives were successfully met through the implementation of the methodology.

The findings derived from this study indicate that it is possible to improve power factor management on deep-level mines through daily monitoring, reporting, and notification tools. These tools promote proactive action towards decreasing penalties on excess reactive energy charges and reducing the operational costs attributed to electricity usage. However, it is important to note that alongside these tools, where feasible, adequate power factor correction (PFC) initiatives should be implemented to realise sustained improvement in power factor management.

ACKNOWLEDGEMENTS

I would like to thank the following parties for their support and guidance throughout the duration of this study.

- Firstly, I would like to thank the Lord for being my foundation of strength and blessing me with my talents and the loved ones in my life.
- Thank you to ETA Operations (Pty) Ltd for the opportunity, financial assistance, and support, without which this study would not have been possible.
- To my study leader, Dr. Johann van Rensburg, thank you for your time, mentorship, and guidance throughout my studies.
- To Dr. Jean van Laar, thank you for your input and open-door policy, it is greatly appreciated.
- To my friends and colleagues, thank you for your support and valuable insights. Your encouragement during my studies is greatly appreciated.
- To my parents, Danoe and Elbrey, thank you for your unwavering support and belief in me. Words cannot express how thankful I am for the time and effort both of you have invested into my development to provide me with the necessary opportunities to excel in life. Thank you for making me the person I am today.
- Thank you to my sister, Deidré, for her continued encouragement and support. You have always set a great example of working hard to achieve your goals and to persevere when faced with difficulty.
- To my parents-in-law Tielman and Lizette, thank you for your incredible support and positivity. I am grateful to have the both of you in my life.
- Lastly, I would like to thank my wife, Minke, for her unconditional love, care, and support throughout my studies. You have been a pillar of strength in both the challenging and joyful times. You have played an important role in my development as a person by always believing in my abilities and potential. I love you dearly.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
TABLE OF FIGURES	vii
LIST OF TABLES.....	xii
LIST OF EQUATIONS	xiv
LIST OF ACRONYMS.....	xv
LIST OF UNITS.....	xvii
LIST OF SYMBOLS	xviii
1 INTRODUCTION AND LITERATURE REVIEW	2
1.1 Preamble	2
1.2 Gold mining electricity demand and usage in South Africa.....	2
1.3 Electricity generation, load management, and tariff structures in South Africa	6
1.4 Power factor and its potential impact on system operations.....	11
1.5 Power factor management.....	14
1.6 Monitoring and reporting tools for power factor management	17
1.7 Literature review	25
1.8 Problem statement	46
1.9 Objectives.....	46
1.10 System development methodologies	47
1.11 Document overview	52
2 DEVELOPMENT OF POWER FACTOR MONITORING AND REPORTING TOOLS ...	54
2.1 Introduction.....	54
2.2 Stage 1: Performance analysis	54
2.3 Stage 2: Requirements gathering and analysis.....	62
2.4 Stage 3: Design	65
2.5 Stage 4: Development	68
2.6 Stage 5: Testing	68

2.7	Stage 6: Deployment	71
2.8	Stage 7: Upkeep and maintenance	71
2.9	Verification of the methodology	76
2.10	Conclusion	76
3	METHODOLOGY IMPLEMENTATION AND RESULTS	78
3.1	Introduction	78
3.2	Case Study	78
3.3	Post-deployment review	138
3.4	Conclusion	139
4	CONCLUSION AND RECOMMENDATIONS	142
4.1	Summary	142
4.2	Recommendations for future work	146
5	REFERENCES	150
	APPENDIX A: ELECTRICAL GRID BACKGROUND	160
	APPENDIX B: HIGH-LEVEL POD BREAKDOWN	164
	APPENDIX C: ESKOM TARIFFS AND DESCRIPTIONS	165
	APPENDIX D: POWER FACTORS IN INDUSTRY	175
	APPENDIX E: BASIC SCADA EXAMPLE	176
	APPENDIX F: REQUIREMENTS GATHERING AND STUDY TEMPLATES	177
	APPENDIX G: BUSINESS INTELLIGENCE SOFTWARE	180
	APPENDIX H: VERIFICATION EXTENSION	181
	APPENDIX I: VALIDATION EXTENSION	186
	APPENDIX J: POWER FACTOR TRACKING SHEET EXAMPLES	195

TABLE OF FIGURES

Figure 1: Typical gold mine electricity usage breakdown [3].....	3
Figure 2: South African yearly gold production, 1990 - 2021	4
Figure 3: Average mining tariff and tariff increase in South Africa	5
Figure 4: Typical gold mine operating costs [5]	5
Figure 5: Basic load management techniques [15].....	7
Figure 6: Typical South Africa winter and summer profiles [21]	8
Figure 7: Eskom TOU tariff structures for winter and summer [20]	9
Figure 8: Power triangle [25]	11
Figure 9: Typical current and voltage waveforms for linear and non-linear loads.....	14
Figure 10: Ideal load profile with power factor correction.....	15
Figure 11: Normal distribution and standard deviations about the mean	20
Figure 12: Typical control chart	20
Figure 13: Distribution of literature studies considered	27
Figure 14: Year range distribution of literature studies considered	27
Figure 15: High-level system architecture [56]	36
Figure 16: Waterfall SDLC model.....	49
Figure 17: Performance analysis process flow diagram	55
Figure 18: 5WH framework	62
Figure 19: Modification request structure [71]	72
Figure 20: IEEE Maintenance process [86], [87]	73
Figure 21: Waterfall SDLC methodology breakdown	75
Figure 22: Case study power factor impact on excess reactive energy	84
Figure 23: Case study power factor impact on apparent power consumption	85
Figure 24: Case study capacitor bank downtime impact on power factor	85
Figure 25: Case study capacitor bank downtime impact on excess reactive energy consumption	86

Figure 26: Case study power factor cost impact.....	87
Figure 27: System architecture of the web-based power factor monitoring and data visualisation tool	96
Figure 28: System architecture of the power factor daily performance reporting tool.....	96
Figure 29: System architecture of the power factor notification system	97
Figure 30: Integrated system architecture of the power factor tools.....	98
Figure 31: Power factor monitoring and data visualisation dashboard home page	100
Figure 32: Dropdown list for further analysis of the selected POD.....	101
Figure 33: Power factor analysis page	102
Figure 34: Data point inspection on power factor profile	102
Figure 35: Period selection and POD selection dropdown lists.....	103
Figure 36: Period selection dropdown list options	103
Figure 37: Power factor profile options menu	104
Figure 38: Data extraction options.....	104
Figure 39: Power factor report – daily operation POD power factor performance table	106
Figure 40: Power factor report – 14-day operation POD power factor performance table ..	107
Figure 41: Power factor report – daily and historic POD performance profiles.....	108
Figure 42: PTB Notification system	110
Figure 43: PTB notification system – instrumentation box	110
Figure 44: PTB Notification system – notification settings	111
Figure 45: MTB mobile application power factor limit notification	112
Figure 46: MTB mobile application notification history log	113
Figure 47: Web-based monitoring and data visualisation tool output verification – 32-day profile	117
Figure 48: Web-based monitoring and data visualisation tool output verification – daily profile	117
Figure 49: Power factor report – daily performance table values for POD C1.....	118
Figure 50: Power factor report – 14-day performance table values for POD C1	119

Figure 51: Power factor report – 31-day performance table values for POD C1	119
Figure 52: Power factor report – POD C1 daily performance profile	120
Figure 53: Power factor report – daily performance profile output verification	120
Figure 54: Power factor report – POD C1 historic performance profile	121
Figure 55: Power factor report – historic performance profile output verification.....	121
Figure 56: Power factor notification output #1	122
Figure 57: Power factor notification output #2	122
Figure 58: Power factor notification system – data verification profiles of POD C1.....	123
Figure 59: Power factor notification system – raw data verification of POD C1.....	123
Figure 60: Power factor notification system – output verification via the daily performance profile	124
Figure 61: Power factor notification system – output verification via the historic performance profile	124
Figure 62: Power factor notification system – output verification via the data visualisation tool	125
Figure 63: Case study post-implementation power factor impact on excess reactive energy	129
Figure 64: Case study post-implementation capacitor bank downtime impact on average power factor.....	131
Figure 65: Case study post-implementation capacitor bank downtime impact on excess reactive energy.....	131
Figure 66: Case study post-implementation power factor impact on max apparent power consumption.....	132
Figure 67: Case study post-implementation power factor impact on excess apparent power consumption	133
Figure 68: Case study post-implementation power factor cost impact (normalised)	134
Figure 69: Schematic representation of the electrical grid [88]	160
Figure 70: Coal-fired power plant.....	161
Figure 71: High-voltage power lines	162
Figure 72: Distribution substation.....	162

Figure 73: High-level POD split into incomers	164
Figure 74: Eskom tariff booklet listed abbreviations [91].....	165
Figure 75: Eskom tariff booklet listed definitions – section 1 [91].....	166
Figure 76: Eskom tariff booklet listed definitions – section 2 [91].....	167
Figure 77: Eskom tariff booklet listed definitions – section 3 [91].....	168
Figure 78: Eskom tariff booklet Mega Flex charges descriptions [20].....	169
Figure 79: 2021/2022 Eskom Mega Flex non-local authority charges [92].....	170
Figure 80: 2022/2023 Eskom Mega Flex non-local authority charges [20].....	171
Figure 81: Eskom tariff booklet NMD rules [24]	172
Figure 82: 2022/2023 Eskom excess network capacity charges [24].....	173
Figure 83: Eskom electricity bill example.....	174
Figure 84: Typical induction motor load factor versus power factor performance [25].....	175
Figure 85: Typical power factor performance of industrial equipment [25]	175
Figure 86: Overview of a basic SCADA system.....	176
Figure 87: Web-based monitoring and data visualisation tool output verification – 32-day profile Incomer 2.....	182
Figure 88: Web-based monitoring and data visualisation tool output verification – daily profile Incomer 2	182
Figure 89: Web-based monitoring and data visualisation tool output verification – 32-day profile Incomer 3.....	183
Figure 90: Web-based monitoring and data visualisation tool output verification – daily profile Incomer 3	184
Figure 91: Web-based monitoring and data visualisation tool output verification – 32-day profile Incomer 4.....	185
Figure 92: Web-based monitoring and data visualisation tool output verification – daily profile Incomer 4	185
Figure 93: Year-on-year power factor performance of POD H1 – validation of tools.....	186
Figure 94: Year-on-year power factor performance of POD F1 – validation of tools	187
Figure 95: Year-on-year power factor performance of POD G1 – validation of tools	188

Figure 96: Year-on-year power factor performance of POD C1 – validation of tools.....	189
Figure 97: Year-on-year power factor performance of POD B2 – validation of tools.....	190
Figure 98: Year-on-year power factor performance of POD A2 – validation of tools.....	192
Figure 99: Year-on-year power factor performance of POD B1 – validation of tools.....	192
Figure 100: Year-on-year power factor performance of POD I1 – validation of tools	193
Figure 101: Year-on-year power factor performance of POD E1 – validation of tools.....	193
Figure 102: Year-on-year power factor performance of POD A1 – validation of tools.....	194
Figure 103: Year-on-year power factor performance of POD D1 – validation of tools.....	194
Figure 104: POD power factor tracking example	195
Figure 105: POD power factor limit sheet example	195

LIST OF TABLES

Table 1: Eskom reactive energy charge 2022/2023 [20].....	10
Table 2: State of the art matrix	45
Table 3: Performance metrics for power factor analysis	59
Table 4: Performance analysis data sources.....	60
Table 5: Requirements gathering through 5W questions example.....	63
Table 6: List of requirements example	63
Table 7: Requirements analysis example.....	64
Table 8: List of tools and features example	65
Table 9: Tool design specifications example	65
Table 10: Data tool features and software products options	67
Table 11: Verification of the methodology	76
Table 12: Case study performance metrics for power factor analysis.....	79
Table 13: Case study performance metric data sources.....	80
Table 14: Case study operation PODs	81
Table 15: Case study performance metric equations	81
Table 16: Case study Eskom billing periods (June to September).....	82
Table 17: Case study power factor impact on reactive energy and apparent power consumption	82
Table 18: Case study power factor financial impact on reactive energy and demand charges	83
Table 19: Case study requirements gathering through 5W questions.....	89
Table 20: Case study list of requirements	89
Table 21: Case study requirements analysis.....	90
Table 22: Case study list of tools and features	91
Table 23: Web-based monitoring and data visualisation tool design specifications	98
Table 24: Daily performance reporting design specifications.....	99
Table 25: Notification system design specifications.....	99
Table 26: Data validation - data source versus Eskom MAPE.....	114

Table 27: Web-based monitoring and data visualisation tool output verification	116
Table 28: Power factor report – daily performance table output verification.....	118
Table 29: Power factor report – 14-day performance table output verification	119
Table 30: Power factor report – 31-day performance table output verification	119
Table 31: Case study post-implementation impact on reactive energy and apparent power consumption	127
Table 32: Case study post-implementation financial impact on reactive energy and demand charges	128
Table 33: Case study year-on-year average active power consumption.....	130
Table 34: Requirements gathering through 5W questions template	177
Table 35: List of requirements template	178
Table 36: Requirements analysis template.....	178
Table 37: List of tools and features template.....	179
Table 38: Free Business Intelligence (BI) software options	180
Table 39: Web-based monitoring and data visualisation tool output verification – Incomer 2	181
Table 40: Web-based monitoring and data visualisation tool output verification – Incomer 3	183
Table 41: Web-based monitoring and data visualisation tool output verification – Incomer 4	184

LIST OF EQUATIONS

Equation 1: Power factor ratio	11
Equation 2: Power factor ratio phase angle	12
Equation 3: Power factor non-linear relationship	12
Equation 4: Sample mean	21
Equation 5: Alternative sample mean expression	21
Equation 6: Population mean	21
Equation 7: Sample standard deviation	22
Equation 8: Population standard deviation	22
Equation 9: Control chart sample CL	22
Equation 10: Control chart sample UCL	22
Equation 11: Control chart sample LCL	22
Equation 12: Control chart population CL	23
Equation 13: Control chart population UCL	23
Equation 14: Control chart population LCL	23
Equation 15: Non-excess reactive energy	57
Equation 16: Excess reactive energy	57
Equation 17: Reactive energy charge	57
Equation 18: Maximum demand	58
Equation 19: Power factor expression at unity with excess apparent power considered	58
Equation 20: Excess apparent power	58
Equation 21: Excess network demand charge	58
Equation 22: Error percentage	69
Equation 23: Mean absolute percentage error (MAPE)	70

LIST OF ACRONYMS

Abbreviation	Description
AC	Alternating Current
ANN	Artificial Neural Network
APFC	Active/Automatic Power Factor Correction
BTM	Behind the Meter
CL	Centre Line
CSV	Comma Separated Values
DSM	Demand Side Management
ESS	Energy Storage System
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IRP	Integrated Resource Plan
ISO	International Organisation for Standardisation
LCL	Lower Control Limit
MAPE	Mean Absolute Percentage Error
MTB	Management Toolbox
NASA	National Aeronautics Space Administration
NMD	Notified Maximum Demand
PDF	Portable Document Format
PF	Power Factor
PFC	Power Factor Correction
PFM	Power Factor Management
PLC	Programmable Logic Controller
POD	Point of Delivery
PPFC	Passive Power Factor Correction
PTB	Process Toolbox

Abbreviation	Description
PV	Photovoltaic
TOU	Time of Use
RF	Radio Frequency
RTB	Reporting Toolbox
SCADA	Supervisory Control and Data Acquisition
SDLC	System/Solution Development Life Cycle
SQL	Structured Query Language
SMS	Short Message Service
TCP	Transmission Control Protocol
TQM	Total Quality Management
UCL	Upper Control Limit
VAT	Value Added Tax
XML	Extensible Markup Language

LIST OF UNITS

Symbol	Description	Unit
\$	Measure of currency	American Dollar
A	Measure of electric current	Ampere
c	Measure of currency	South African cent
g	Measure of mass	Gram
G	Denotes 1×10^9	Giga
h	Measure of time	Hour
k	Denotes 1×10^3	Kilo
m	Measure of distance	Metre
min	Measure of time	Minute
M	Denotes 1×10^6	Mega
R	Measure of currency	South African Rand
V	Measure of electric potential	Volt
W	Measure of power	Watt
Wh	Measure of energy	Watt-hour

LIST OF SYMBOLS

Symbol	Description	Unit
P	Active power	W
P_{Total}	Total active power	W
$P_{At\ max\ S}$	Active power at maximum apparent power	W
S	Apparent power	VA
S_{Excess}	Excess apparent power	VA
S_{Max}	Maximum apparent power	VA
Q	Reactive power	VA _r
Q_{Excess}	Excess reactive power	VA _r
$Q_{Non-excess}$	Non-excess reactive power	VA _r
Q_{Total}	Total reactive power	VA _r

CHAPTER 1

1 INTRODUCTION AND LITERATURE REVIEW

1.1 Preamble

This chapter provides an overview of South African deep-level gold mines in terms of electricity consumption and challenges faced by the industry. Insight into the South African electricity generation and tariff structures are also discussed.

Power factor (PF) and its impact on the mining industry is presented with relevant background regarding web-based monitoring and performance reporting. A literature review was conducted to explore PF management from which the need for the study was derived.

The study objectives were defined based on the insights and shortcomings identified from the existing literature. An outline of system development life cycle (SDLC) methodologies and background on the waterfall SLDC are presented. Chapter 1 concludes with an overview of the study.

1.2 Gold mining electricity demand and usage in South Africa

The mining industry in South Africa accounts for over 14% of the country's energy consumption¹. Within this industry, electricity accounts for 58% of the total energy demand [1]. Gold mines are responsible for almost half of the mining industry's electricity usage which equates to around 7% of the country's total electricity consumption [2].

Therefore, it is important to understand the electricity usage on mines, especially on gold mines, and to ensure adequate management to reduce wastage.

1.2.1 Overview of electricity demand and usage on deep-level gold mines

The typical electricity usage breakdown of a gold mine in its various systems is depicted in Figure 1. The systems responsible for the largest electricity consumption include ventilation and refrigeration (28%), compressed air (19%), and pumping (16%) [3].

¹ Eskom, 'Group interim results', 2021. <https://www.eskom.co.za/investors/integrated-results/> (accessed Aug. 10, 2022).

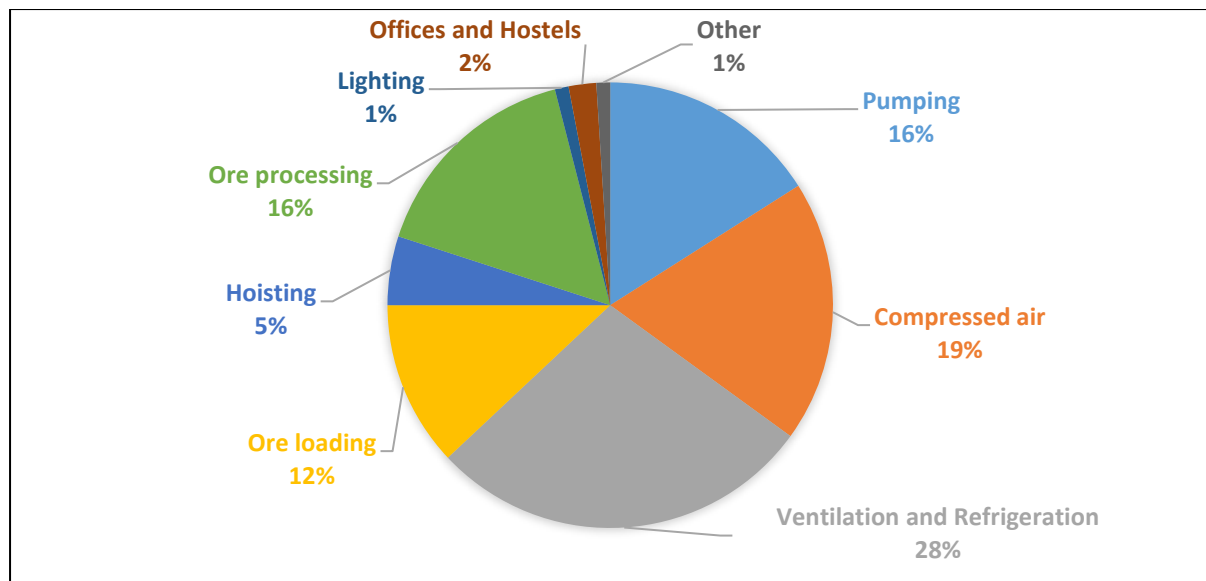


Figure 1: Typical gold mine electricity usage breakdown [3]

Each of the services shown in Figure 1 are essential to production. This breakdown reveals the reliance of gold mines on the continuous supply of electricity to perform daily operations. Unfortunately, the electricity supply in South Africa has become less reliable due to challenges faced by Eskom, the country's primary supplier of electricity [2], [4]. Further background on Eskom and its challenges concerning electricity generation are discussed in Section 1.3.1.

1.2.2 Challenges in South African gold mining

The gold mining sector in South Africa faces many challenges. The sector has seen a major decline in production over the past few decades. Annual gold production has decreased from 619 201 kg (1993) to 100 000 kg in 2021². Historic data indicates that modern gold production in South Africa has deteriorated by a staggering 87% when compared to the volume of gold produced in 1980³. Figure 2 showcases the decline in gold production from 1990.

² CEIC, 'South Africa Gold Production', 2018. <https://www.ceicdata.com/en/indicator/south-africa/gold-production> (accessed Aug. 11, 2022).

³ M. McCrae, 'The stunning collapse of gold production in South Africa', 2015. <https://www.mining.com/the-stunning-collapse-of-gold-production-in-south-africa/> (accessed Aug. 11, 2022).

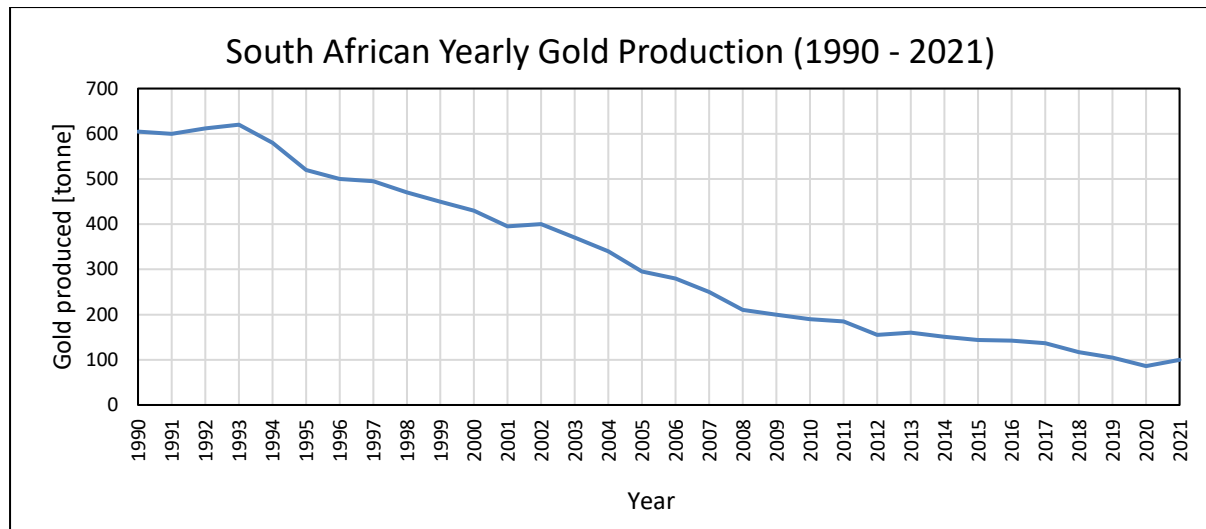


Figure 2: South African yearly gold production, 1990 - 2021⁴

It is evident from this data that the modern-day gold mining industry in South Africa is struggling to remain productive. There are various factors contributing to this decline such as: diminishing ore grades, industrial action (protests), and weakening in gold prices [5].

The productivity of South Africa gold mines has been waning in recent years. This can be attributed to factors such as increased operating depth and travel time to working areas [6]. South Africa has some of the deepest mines in the world that reach depths of up to 4 km [7]. The importance of improving or maintaining production rates becomes evident as mining operations proceed to greater depths [8].

Most of the high-grade gold deposits in South Africa have been exhausted, leading to mines exploiting lower grades. The diminishing ore grade suggests that there is an increase in the energy and resources used per kg of gold produced [9]. Hence, more ore needs to be mined for less retrieved gold.

The impact of the increase in energy required to mine on the operating costs is amplified by escalating electricity prices. As seen in Figure 3, from 2003 to 2022, there was an increase of 767% in the average electricity tariff⁵.

⁴ Adapted from: CEIC, 'South Africa Gold Production', 2018. <https://www.ceicdata.com/en/indicator/south-africa/gold-production> (accessed Aug. 11, 2022).

⁵ Eskom, 'Tariff history', 2022. <https://www.eskom.co.za/distribution/tariffs-and-charges/tariff-history/> (accessed Aug. 26, 2021).

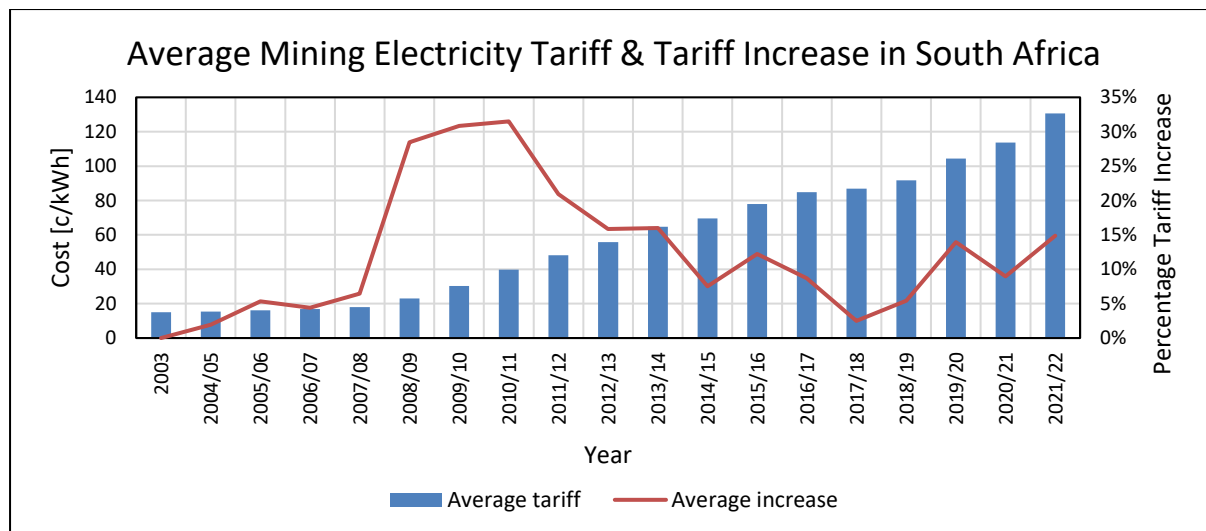


Figure 3: Average mining tariff and tariff increase in South Africa⁶

Gold mines are facing surges in operating costs of which labour and electricity are large contributors. This substantial rise in recent years has amplified the weakening financial performance of gold mines in South Africa [10]. This combined with the decline in production has led to many South African gold mines becoming marginal operations⁷. Figure 4 depicts the typical operating costs of a gold mine.

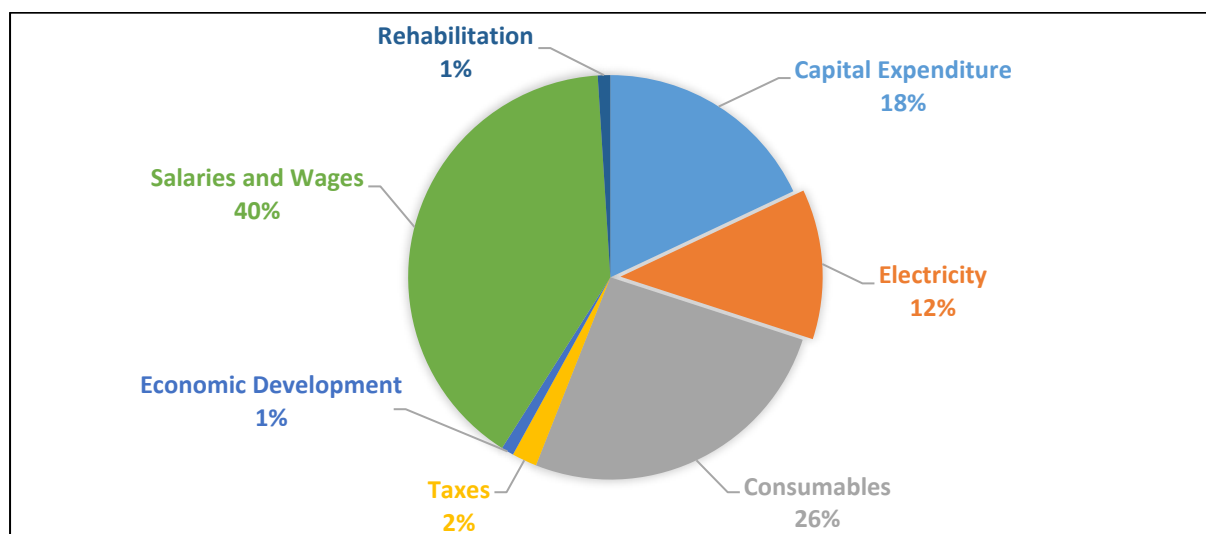


Figure 4: Typical gold mine operating costs [5]

The major expenses outlined in Figure 6 are wages and salaries, consumables, capital expenditure, and electricity. Unfortunately, it is problematic to cut down on wages and salaries, consumables, and capital expenditure due to profitability and regulatory concerns [5].

⁶ Adapted from: Eskom, 'Tariff history', 2022. <https://www.eskom.co.za/distribution/tariffs-and-charges/tariff-history/> (accessed Aug. 26, 2021).

⁷ K. Crowley, 'South African Gold on the Brink With Half of Mines Losing Money', 2015. <https://www.bloomberg.com/news/articles/2015-09-08/south-africa-gold-industry-fades-as-margin-squeeze-erodes-output> (accessed Aug. 12, 2022).

However, it is viable to reduce the electricity portion of the operational costs illustrated in Figure 4. This is critical within the South African context considering the upward trend in electricity prices, as seen in Figure 3. These prices will most likely continue to increase at rates exceeding inflation for the near future [5].

Therefore, gold mines need to prioritise methods which compensate for the ever-increasing operational costs and dwindling profits. Lowering the electricity demand will assist in reducing the impact of this major operational expense on profitability [5]. This may prove to be vital for the sustainability of gold mines, as they can improve their management of operational expenses by reducing wastage.

1.3 Electricity generation, load management, and tariff structures in South Africa

1.3.1 Electricity generation and challenges in South Africa

Eskom is South Africa's main electricity provider and generates approximately 95% of the country's electricity and nearly 45% of the electricity used in Africa⁸.

Eskom's ability to meet the country's electricity demand has been questioned in recent years, particularly with the implementation of country-wide load shedding [11]. The current system is often left vulnerable to unplanned outages as Eskom struggles to maintain a sufficient reserve margin of 15%⁹.

Consequently, large consumers are usually targeted with load curtailment when the electrical grid is strained and demand reduction is required. This combined with Eskom's consistent increases in electricity prices, as depicted in Figure 3, has a substantial impact on the mining industry. This is a major concern for the gold mining sector considering their heavy reliance on electricity [2], [12] as outlined in Section 1.2.1. Further background regarding the electrical grid and some of its key components are outlined in Appendix A.

It is apparent that there has been a significant decline in the energy security of South Africa [11]. Therefore, it is critical to induce changes that will assist in ensuring supply exceeds demand. The two core approaches to this problem are to increase supply and manage

⁸ Department of Public Enterprises (DPE), 'Eskom', 2019. <https://dpe.gov.za/state-owned-companies/eskom/> (accessed Aug. 13, 2022).

⁹ K. Crowley and A. Janse van Vuuren, 'Eskom Declares Power Emergency, Asks South Africa to Cut Use', 2014. <https://www.bloomberg.com/news/articles/2014-02-20/eskom-declares-power-emergency-and-asks-south-africa-to-cut-use> (accessed Aug. 13, 2022).

demand. Unfortunately, the process of increasing supply is time-consuming and requires considerable capital investment¹⁰.

Thus, load management should be prioritised while supply increase projects are being developed and implemented. It is important to note that load management should be implemented as a continuous initiative and considered part of the long-term approach alongside supply increase projects to enable Eskom to overcome the current supply and demand issue. The following section will briefly discuss load management and how it applies to deep-level gold mines.

1.3.2 Load management on deep-level gold mines

Load management is the process by which power utilities and consumers attempt to reduce peak electrical load demand in order to improve the efficiency of the electrical generation system [13], [14], [15], [16]. The core concept of load management entails shifting the electrical load from high-demand periods to lower demand periods to delay or avoid the installation of extra capacity for the power utilities to meet peak demand [14], [16].

Load management techniques have been utilised since the 1980s and consist of three basic types, namely peak clipping, valley filling, and load shifting [15], [16]. Figure 5 illustrates the concepts of these approaches to load management.

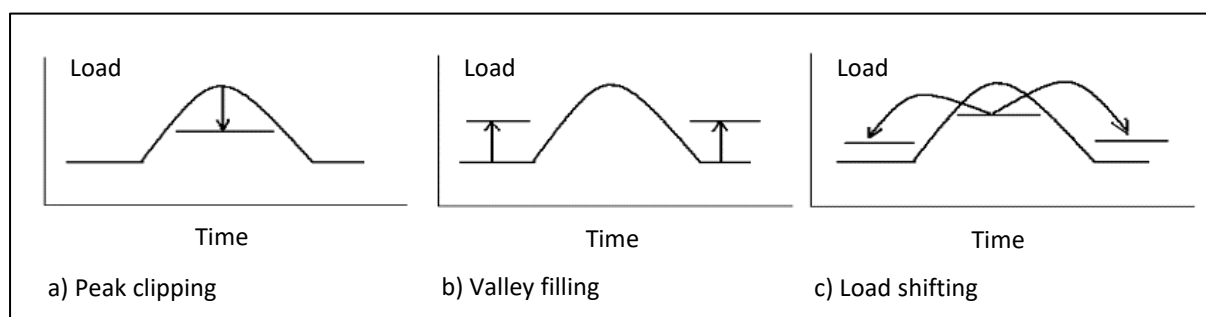


Figure 5: Basic load management techniques [15]

Peak clipping entails the reduction of the electrical load during the peak demand periods, while valley filling focuses on building loads during the off-peak periods. Load shifting involves moving a system's load from peak demand to off-peak periods without altering the total consumption and combines the benefits of peak clipping and valley filling [15].

¹⁰ A. Routledge, 'South Africa's power grid is under pressure: the how and the why', 2021. <https://theconversation.com/south-africas-power-grid-is-under-pressure-the-how-and-the-why-170897> (accessed Aug. 13, 2022).

Consumers are typically incentivised to implement these techniques by utilities via electricity time of use (TOU) rates [13], [14]. This encourages consumers to reduce their electricity consumption during peak demand periods, as they will save on electricity costs [14], [16].

It is, therefore, evident that load management promotes electricity conservation, as it helps to reduce peak load demand as well as the total electricity consumption [15]. This can assist Eskom with maintaining and improving their reserve margins when implemented [2]. Therefore, load management is an important initiative to be employed by large electricity consumers and has been proven to deliver substantial cost savings in return [17], [18], [19].

Load management needs to be applied by large electricity consumers to achieve substantial results [2]. Gold mines are, therefore, ideal targets for such initiatives considering their heavy reliance on electricity as shown in Section 1.2.

1.3.3 Eskom electricity tariff structures

This section provides an overview of Eskom's electricity tariffs in relation to the mining industry. Eskom's electricity TOU tariffs are based on the electricity demand patterns for winter and summer months in South Africa [20].

As indicated in Section 1.3.2, these tariffs are used to incentivise load management initiatives. Figure 6 illustrates the typical load profiles for Eskom.

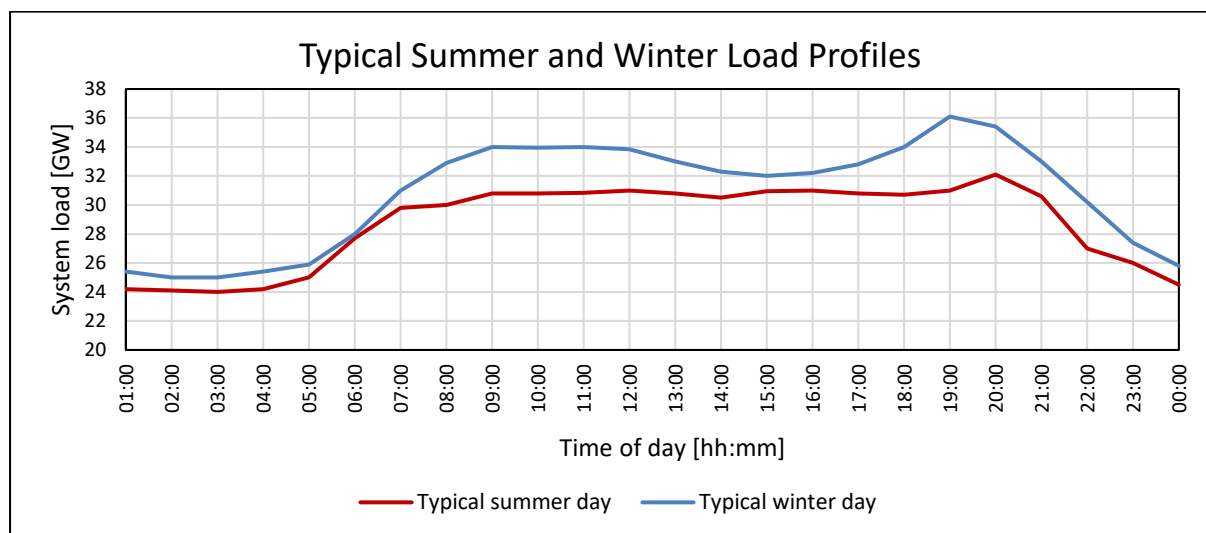


Figure 6: Typical South Africa winter and summer profiles [21]

It is evident from the load profiles that the demand is at its highest during the morning and evening periods [21]. Eskom defines these intervals as high-demand periods and charge consumers more for electricity usage during this time. Eskom refers to these electricity prices as active energy charges which are measured in cents per kilowatt hour (c/kWh) [20].

Figure 7 illustrates Eskom's TOU tariff structure for large electricity consumers which is divided into summer (low-demand season) and winter (high-demand season).

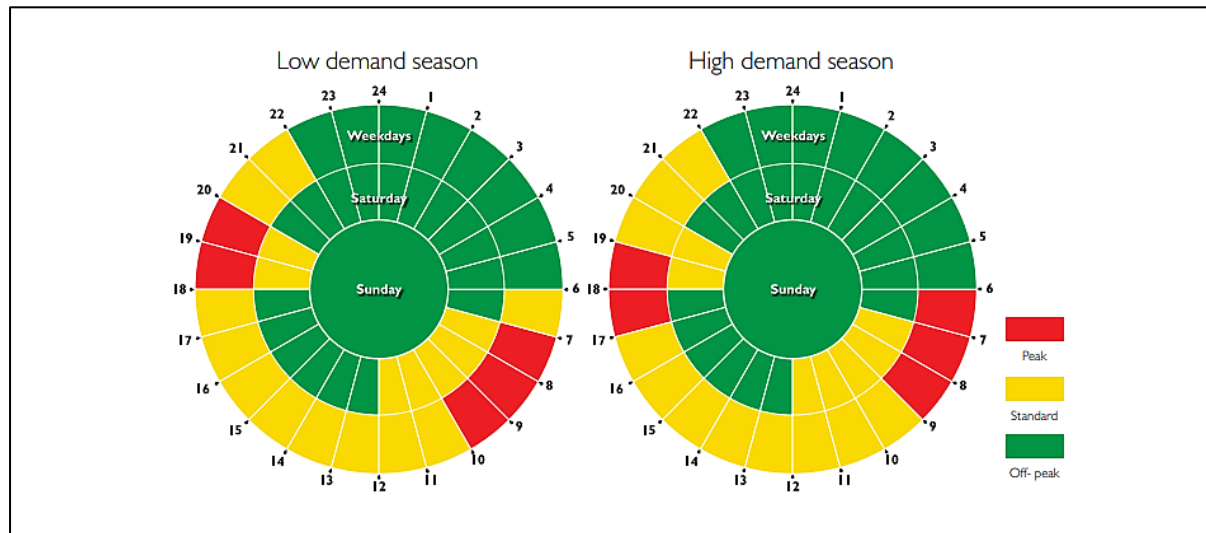


Figure 7: Eskom TOU tariff structures for winter and summer [20]

As seen from Figure 7, these tariffs are segmented into off-peak (low demand), standard (normal demand), and peak (high demand) periods. The mining industry's electricity charges during these periods are based on Eskom's Mega Flex non-local authority charges tariff structures.

The Mega Flex tariffs are only applicable to customers with a notified maximum demand (NMD) greater than 1 MVA and that are within Eskom's licensed area of supply (direct customers). NMD refers to the contracted maximum demand that was notified in writing by the consumer per point of supply (POD) and accepted by Eskom [20]. The POD can be further divided into incomers and feeders as presented in Appendix B.

Eskom defines a POD as: "POD/point of supply, means either a single point of supply or a specific group of points of supply on Eskom's System from where electricity is supplied to the customer by Eskom or from where the customer supplies electricity to Eskom's System located within a single substation, at which electricity is supplied to the customer at the same declared voltage and tariff. Note: This can be a metering or summation point" [20].

Eskom's electricity billing is based on the energy usage measured at the POD. The Eskom account is described by Eskom as: "Account means the invoice received by a customer for a single POD or if consolidated, multiple points of delivery for electricity supplied and/or use of the System" [20]. The abbreviations, definitions, and descriptions of the various charges as described by Eskom is presented in Appendix C.

Additional to the active energy charges are transmission network charges, distribution network charges, ancillary service charges, electrification and rural network subsidy charges, affordability subsidy charges, service charges, administration charges, and reactive energy charges [20]. The 2021/2022 and 2022/2023 tariffs for these various charges can be viewed in Appendix C.

An additional energy charge supplementary to the kW and kVA demand charges is the reactive energy charge. Reactive energy charges are penalties on reactive energy consumption supplied in excess of 30% (PF of 0.96 or less) of the recorded active energy measured in kilowatt-hours (kWh) during peak and standard electricity usage periods [20], [22].

The excess reactive energy is calculated per 30-minute integrating period, accumulated for the billing month and measured in reactive kilovolt-ampere-hour (kVAh) [20]. Referring to Table 1, it is important to note that these penalties on reactive energy are only applicable during the high-demand season (1 June to 31 August on the Eskom electricity bill).

Table 1: Eskom reactive energy charge 2022/2023 [20]

Reactive Energy Charge [c/kVAh]			
High Season (Winter)		Low Season (Summer)	
-	VAT included	-	VAT included
21.03	24.18	0.00	0.00

Additional to these penalties, poor PF or high reactive energy consumption also increases the apparent energy demand charges, which are billed monthly throughout the year [23]. The apparent power consumption is the total power consumption measured in kilovolt-ampere (kVA). This can lead to the agreed NMD being exceeded which leads to additional penalties that are expensive in comparison to the standard demand charges and reactive energy penalties [20]. It should be noted that there is a 5% deadband on the NMD which implies that penalties will be allocated if the exceeded demand is more than 5% of the agreed NMD [24]. The charges applicable for exceeding the NMD are presented in Appendix C.

Therefore, it is crucial for gold mines to be vigilant with regards to their reactive energy consumption during the winter months to avoid penalties as well as during the rest of the year considering the impact it could have on their energy charges and NMD. It is evident that high reactive energy has the potential to inflate the electricity costs for gold mines if not monitored and addressed accordingly. Section 1.4 will provide background on power factors and its potential impact on Eskom and gold mines.

1.4 Power factor and its potential impact on system operations

It is important to comprehend what PF is to ensure that it is correctly managed considering the potential impact it may have on electricity bills, especially for deep-level gold mines. Aside from its impact on electricity costs, other operational influences will also be considered.

1.4.1 The fundamentals of power factor

The PF describes the percentage of electricity that is being utilised to perform useful work and is defined as the ratio of active power (kW) to apparent power (kVA) as expressed in Equation 1 [22], [25].

Equation 1: Power factor ratio

$$\text{Power Factor (PF)} = \frac{\text{Active Power (P)}}{\text{Apparent Power (S)}} \text{ or } \frac{\text{kW}}{\text{kVA}}$$

Apparent power signifies the total power consumption and consists of two components, namely active and reactive power. Active power is the power devices use to perform useful work and is transferred from electrical energy to another form of energy such as mechanical energy or heat. Reactive power generates and maintains the magnetic fields to produce the necessary flux that allows for the operation of inductive equipment. Examples of inductive loads are transformers, ballast-type lighting, AC motors, and induction furnaces [12], [25], [26].

Reactive power yields no productive work; thus, an inductive motor will draw almost no active power (productive power) when it is supplied with power but has no load on its shaft. The power used by the motor during this period is almost entirely reactive power. The reactive power is reduced and the active power is raised as the load on the shaft of the motor increases [25]. Appendix D provides an overview of how the load on a motor's shaft influences the PF.

The total power or apparent power is determined through the vector sum of the active power and reactive power [22]. This is illustrated by the power triangle in Figure 8.

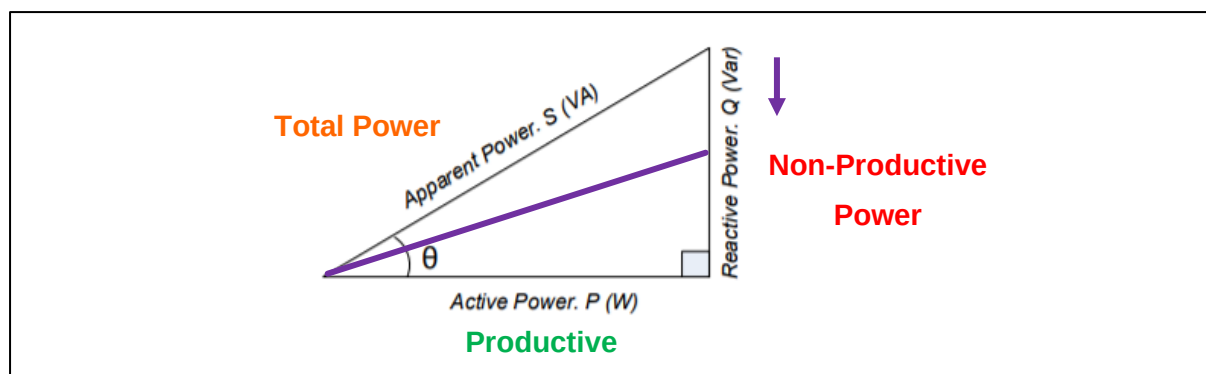


Figure 8: Power triangle [25]

From the power triangle, it can be derived that the PF of a load is also represented by the cosine of the phase angle θ between the active power and apparent power. Thus, the following equation also holds true [25], [26].

Equation 2: Power factor ratio phase angle

$$\text{Power Factor (PF)} = \cos(\theta) = \frac{kW}{kVA}$$

Furthermore, as the phase angle θ or the reactive power is reduced, the apparent power also declines. The relationship between active power (P), reactive power (Q), and apparent power (S) is non-linear and can be expressed as follows [25]:

Equation 3: Power factor non-linear relationship

$$\text{Apparent power (S)}^2 = \text{Active power (P)}^2 + \text{Reactive power (Q)}^2$$

In conclusion, the perfect PF is close to 1 (unity), which implies that 100% of the power being supplied is used to perform productive work. Therefore, a PF of 0.69 infers that only 69% of the power is converted into productive work and 31% of the power into non-productive work (reactive power) [25]. From this, it is evident that a high PF should be maintained to reduce wastage in a system and plays a central role in reducing the strain on the electrical grid. Section 1.4.2 further explores the influence of power factors on Eskom's supply network and the system performance of gold mines.

1.4.2 The potential impact of poor power factor on Eskom and gold mines

Electric motors introduce inefficiencies, expressed by the PF, into the electricity supply network by drawing additional current. This in turn places added strain on Eskom as it increases the load on their switchgear and distribution network as well as the consumer's [25]. The typical un-corrected PF of various equipment used in different industries is presented in Appendix D.

Typically, the un-corrected PF in industrial facilities is around 0.8, which implies that a 1 MVA transformer can only supply 800 kW, or from a 100 A supply only 80 A drawn from the consumer is useful. Thus, power utilities such as Eskom need to generate significantly more current than what is theoretically required [25].

This excess current leads to added stress on the electrical infrastructure such as the transformers, cables, and generators. Therefore, it is crucial to put measures in place to improve the PF of the load or the installed equipment and sub-circuit wiring of the power station will need to be larger than necessary. This results in increased capital expenditure to upgrade

the existing infrastructure as well as higher transmission and distribution losses throughout the whole electricity supply network [25], [26].

In an attempt to discourage this wasted power, electricity suppliers have resolved to penalise consumers on their electricity bill by means of reactive energy charges and notified maximum demand charges [12], [25], [26] as discussed in Section 1.3.3.

Electric motors are generally used in industrial processes to drive ventilation fans, fridge plants, pumps, and conveyors [25]. Hence, they play an integral role in mining and mineral processing¹¹. Gold mines are, therefore, highly susceptible to these electricity penalties due to their heavy reliance on electricity and use of electric motors which inherently have power factors below Eskom's prescribed PF of 0.96.

Apart from an increase in electricity bills, poor PF can also influence the general system performance of a gold mine. Some of these negative impacts include [12], [22], [25], [26], [27], [28]:

- Reduced system operating characteristics
 - Increased line losses and reduced voltage
- Reduced equipment efficiency and, therefore, overall system efficiency
 - Reduced system capacity utilisation
- Reduced equipment life
 - Increased electrical load on cables and electrical components
- Reduced system capacity
 - Higher kVA loading on source generators, transformers, and power cables.

These effects result in increased capital expenditure that expand the network capacity to compensate for poor PF. It is evident that poor PF is detrimental to the electricity supply capabilities of Eskom and the performance of gold mines in terms of system efficiency. Therefore, it is imperative that gold mines manage their PF to reduce electricity costs, improve system performance and reduce the strain on Eskom's supply network. The following section will examine power factor management (PFM).

¹¹ S. Fiscor, 'Motor technology for mining applications advances', 2009. <https://www.coalage.com/features/motor-technology-for-mining-applications-advances/> (accessed Aug. 27, 2022).

1.5 Power factor management

The previous section highlighted the impact of poor PFM on Eskom's ability to supply and meet electricity demand as well as the influence PFM may have on the operational efficiency and electricity costs of gold mines. This section will provide background on the various ways in which PF can be corrected and managed. Furthermore, a general overview regarding the current PFM approach on South African deep level mines will be provided.

1.5.1 Power factor correction

The two primary causes of poor PF or high reactive energy are distortion and displacement in the electric signal. Distortion is denoted by the change in the shape of the signal's original waveform and is generally caused by non-linear loads. Displacement, however, occurs when the voltage and current waveforms of a circuit are out of phase and are usually present in linear loads¹².

Linear loads have a matching sinusoidal profile in terms of their current and voltage waveforms while non-linear loads have different waveforms due to the current being drawn at different frequencies¹³. Figure 9 shows the current and voltage waveforms for a typical linear and non-linear load.

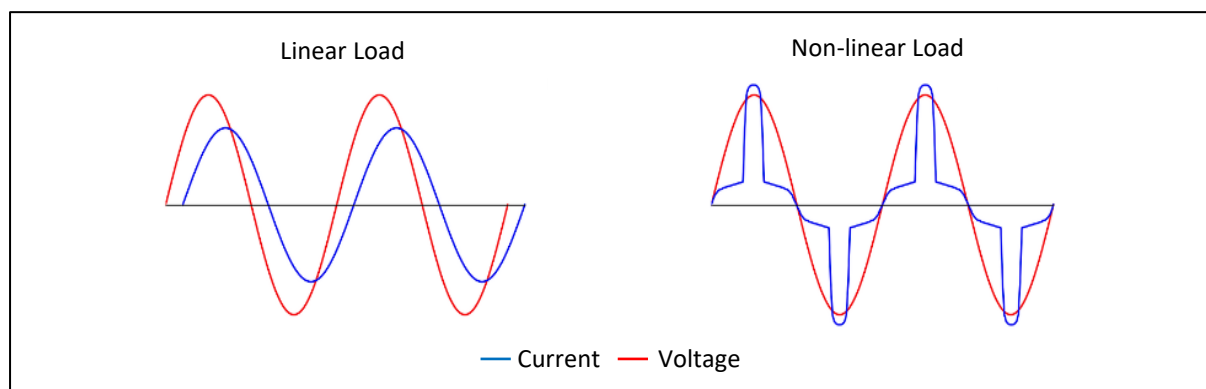


Figure 9: Typical current and voltage waveforms for linear and non-linear loads¹⁴

PFC is the process in which the PF of an AC circuit is brought close to unity by means of reducing the amount of reactive energy or through artificial compensation. The reactive energy can be reduced by eliminating unloaded transformers and motors or by preventing the supply of voltage to equipment in excess of the rated voltage. Artificial compensation of reactive energy can be realised via PFC equipment [25], [27]. Figure 10 illustrates the ideal load profile

¹² T. Hudson, 'Power Factor Correction (PFC) Explained', 2022. <https://www.monolithicpower.com/en/power-factor-correction> (accessed Sep. 05, 2022).

¹³ Passive-components.eu, 'Introduction to Power Factor Correction PFC Capacitors and Circuits', 2022. https://passive-components.eu/an-introduction-to-capacitor-based-power-factor-correction-circuits/#split_content (accessed Sep. 05, 2022).

¹⁴ Adapted from: Passive-components.eu, 'Introduction to Power Factor Correction PFC Capacitors and Circuits', 2022. https://passive-components.eu/an-introduction-to-capacitor-based-power-factor-correction-circuits/#split_content (accessed Sep. 05, 2022).

with PFC where the current and voltage are in the same phase and have a similar sinusoidal waveform.

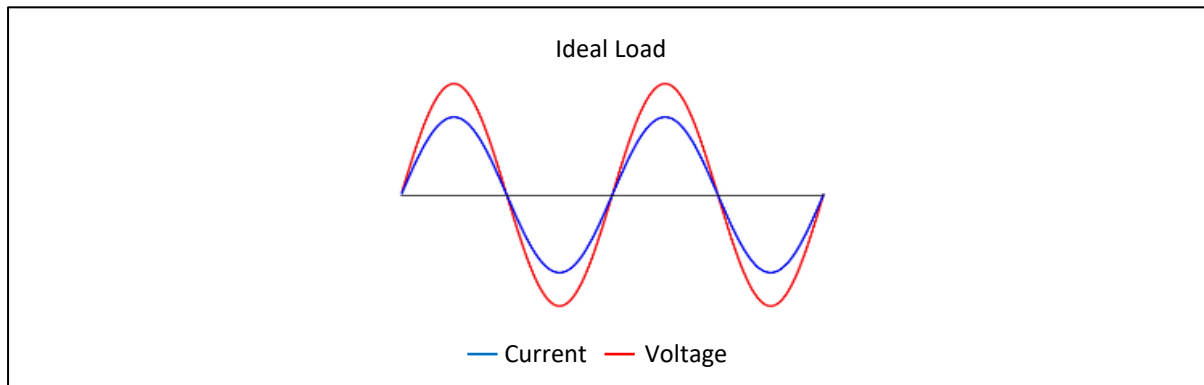


Figure 10: Ideal load profile with power factor correction¹⁵

There are two approaches to solving distortion issues, namely passive power factor correction (PPFC) and active power factor correction (APFC). PPFC improves the PF by implementing passive filters which filter out harmonic distortions in the waveforms. In general, this is only implemented on low-power applications. Conversely, APFC utilises a switching converter to reshape the distorted current waveform into a sinusoidal wave and is considered the best option between the two approaches. However, APFC adds more complexity to the circuit design and is, therefore, more difficult to integrate¹⁶.

Phase displacement between the current and voltage are commonly addressed by implementing external reactive components that compensate for the total reactive energy of the circuit. In practice, this is achieved through the employment of rotary equipment such as phase advancers, synchronous motors, and synchronous condensers or by means of PFC capacitors. However, PFC is commonly used as a secondary function with the utilisation of auto-synchronous motors [25].

Capacitors are a simple approach to negating the negative effects of displacement issues on the PF due to capacitors pulling the current's wave phase forward and inductors dragging it back. Therefore, the addition of capacitors with the correct impedance to a system with an inductive load will pull the current's wave phase forward until it is in phase with the voltage, improving the PF and reducing the reactive energy¹⁷.

¹⁵ Adapted from: Passive-components.eu, 'Introduction to Power Factor Correction PFC Capacitors and Circuits', 2022. https://passive-components.eu/an-introduction-to-capacitor-based-power-factor-correction-circuits/#split_content (accessed Sep. 05, 2022).

¹⁶ T. Hudson, 'Power Factor Correction (PFC) Explained', 2022. <https://www.monolithicpower.com/en/power-factor-correction> (accessed Sep. 05, 2022).

¹⁷ T. Hudson, 'Power Factor Correction (PFC) Explained', 2022. <https://www.monolithicpower.com/en/power-factor-correction> (accessed Sep. 05, 2022).

A capacitor is a device that stores electrical energy and releases the energy at a later time. Capacitors are connected in parallel to motor circuits and can be applied at the switchboard, distribution panel, or starter to achieve PFC [25].

The two main correction methods with capacitor banks are fixed and central PFC. Fixed capacitor correction provides a constant amount of reactive power to an electrical system and is usually applied to individual motor loads. Conversely, central capacitor correction is applied to electrical systems with variable loads and is commonly connected to the main point of power distribution. The PF is continuously monitored by a microprocessor-based relay which also controls the switching of the capacitors. The relay connects the capacitors based on a pre-set lower limit, which is typically around 0.95 [25].

Fixed capacitor banks are generally the preferred PFC method, as they are more economical to implement and require minimal maintenance. Furthermore, they are compact, highly efficient, and convenient to install. Fixed capacitors are commonly used in industry due to their simplicity and aforementioned advantages [12], [25].

It should be noted that harmonic distortion can drastically reduce the lifespan of capacitor banks; therefore, combining the harmonic filtering and capacitor banks for PFC is advised¹⁸.

1.5.2 Power factor management on South African deep-level gold mines

Historically, the need for industrial and mining PFC equipment in South Africa has been of little consequence. However, this changed in 2011 when Eskom introduced penalties on poor PF. The need for PFM has since been driven by the electricity tariffs associated with reactive energy consumption and power factors [29].

Numerous large mining and industrial customers have outdated PFC equipment that were installed in the late nineties. A large portion of this equipment is out of commission due to lack of maintenance or has been rendered inadequate due to the expansion of the electrical network. This deterioration in PFC equipment can be partly attributed to the absence of financial incentives over the years and has, therefore, contributed to the mounting strain on the Eskom electrical grid [29], [30].

However, as outlined in Sections 1.2.2 and 1.3.1, the escalating electricity prices over the last few decades combined with Eskom's limited generation capacity has made PFM increasingly important in South Africa, especially considering the reliance of deep-level gold mines on

¹⁸ Passive-components.eu, 'Introduction to Power Factor Correction PFC Capacitors and Circuits', 2022. https://passive-components.eu/an-introduction-to-capacitor-based-power-factor-correction-circuits/#split_content (accessed Sep. 05, 2022).

electricity to operate. Both the mining sector and Eskom stand to benefit from improved PFM. For this reason, it is important to explore opportunities to improve PFM on deep-level mines that are economical and simple to implement within the available infrastructure.

1.6 Monitoring and reporting tools for power factor management

As mentioned in Section 1.5.2, the opportunity exists to improve the outdated PFM strategy employed on deep-level mines. The integration of PFM tools alongside the current PFC infrastructure may be considered to enhance the existing management strategy. These tools include:

- web-based monitoring,
- performance reporting, and
- three-sigma control charts combined with
- a notification system

may prove to be beneficial in improving PFM on deep-level mines. The utilisation of these tools will be explored in the following section.

1.6.1 Web-based monitoring

Monitoring is the process of systematically observing and measuring the operation of a system to detect changes over a period of time. Data collection at regular intervals is essential to this process, as it enables comparable conclusions to be made based on the data, thereby facilitating the identification of deviations from the desired sequence to allow the necessary intervention to take place and halt irregular operation [31].

Research has shown that power quality, such as power factors, is a concern because it results in various industries experiencing considerable annual revenue loss [32], [33]. Advances in metering technology have made it easier for industrial facilities to benefit from an integrated power monitoring system. The accessibility of tools that ensure high power quality can be supplied has improved. This allows improved accessibility to the integration and use of the various technologies to ensure processes operate continuously and reliably at a reasonable cost [34], [35].

Leveraging advances in monitoring technologies is a form of PFM that improves electrical system management. This allows engineers working at various locations to resolve power quality issues and improve energy management enterprise-wide from remote sites. This can be achieved through remote shared access to real-time and historical operational data [34].

Web-based monitoring is prevalent in modern-day operations and has become a necessity for monitoring systems¹⁹. This provides the user with the ability to monitor their infrastructure from a web browser and observe its performance from anywhere and anytime using a web-enabled device [36].

Technologies such as web-based monitoring can be utilised to monitor the power factors of various deep-level mine operations without having to be present onsite. The ability to monitor the power factors remotely via the internet may also enable more users to observe the PF performance and potentially assist with earlier fault detection and corrective action, ultimately achieving improved PFM.

1.6.2 Performance reporting

Daily performance reporting is a useful tool to track system performance, identify trends, and analyse data. The data and information within the report are typically conveyed via tabular and graphical formats. These usually include a combination of text and visual aids such as tables, charts, and graphs^{20, 21}. The following benefits may be obtained from utilising these tools [37]:

- Early identification of important trends and potential problems,
- improved decision-making based on data,
- improved communication,
- promotes continuous improvement,
- enhances problem-solving and performance, and
- cost efficiency.^{22, 23, 24}

Performance reporting forms an important part of employing effective management due to its influence on decision-making and its ability to promote continuous improvement [37]. Reporting tools have improved with the availability of technology that enables automated data collection from databases and customisation in terms of data visualisation. Performance reporting is a valuable tool for facilities in terms of energy management; it promotes continuous improvement in energy efficiency by tracking energy patterns, facilitating the identification of system issues and the impact of implemented solutions [38].

¹⁹ S. Ramanathan, 'What is Web Based Monitoring', 2010. <https://www.eginnovations.com/blog/web-based-monitoring/> (accessed Sep. 19, 2022).

²⁰ Simplilearn, 'What is Performance Reporting in the Project Management?', 2022. <https://www.simplilearn.com/performance-reporting-article> (accessed Sep. 24, 2022).

²¹ Indeed editorial team, '6 Types of Performance Reports for Projects', 2021. <https://www.indeed.com/career-advice/career-development/performance-reporting> (accessed Sep. 24, 2022).

²² K. Knutson, '6 Benefits of a Good Management Reporting System - Global Investment Strategies', 2018. <https://envivio.com/blog/6-benefits-of-a-good-management-reporting-system/> (accessed Aug. 26, 2021).

²³ Complete Controller, 'Top 5 reason why performance reporting is a priority', 2020. <https://www.completecontroller.com/top-5-reasons-why-performance-reporting-is-a-priority/> (accessed Aug. 26, 2021).

²⁴ M. Memon, '8 Reasons to Make Performance Reporting a Priority in Critical Times', 2022. <https://databox.com/performance-reporting-prioritization-benefits> (accessed Sep. 20, 2022).

The implementation of performance reporting on power factors may, therefore, prove to be beneficial towards improving the management of poor power factors. For example, a performance report may be utilised to rank and prioritise operations based on performance. The ranking of various deep-level mine PODs based on PF, demand charges, and reactive energy charges will enable the prioritisation of critical operations. This will, in turn, promote the continuous improvement of power factors.

Therefore, performance reporting in conjunction with web-based monitoring are valuable tools to consider to improve the management of power factors on deep-level gold mines.

1.6.3 Three-sigma control chart

A control chart is a behaviour chart that studies how a process changes over time. It is used to monitor, control, and improve the performance of a process by examining the variations that occur as well as its sources [39], [40].

The control chart was developed by Dr. Walter Shewhart in the 1920s through research and experiments of various production outputs conducted to improve the quality of telephone equipment. Based on his findings, Shewhart opted to place the control limits of the control chart at three standard deviations (three-sigma) above and below the mean process output to minimise the economic loss from two types of errors²⁵.

The first type of error that can occur is when a control chart classifies a common cause of variation (within statistical normal operation) as a special cause of variation (outside the control limits). This results in wasted resource expenditure to identify a non-existent special cause²⁶, leading to unnecessary changes being implemented on a process that may produce unexpected variations in performance [41].

The second type of error occurs when a special cause of variation is classified as a common cause of variation which, in turn, leads to lost opportunities, as the special source of variation within the process will be ignored and will not be rectified to improve performance [41].

Additionally, Shewhart's implementation of the three-sigma control limits is also statistically supported by the Tchebycheff theorem which states that 89% of any distribution (irrespective of its shape, spread, and centre) will fall within three standard deviations from the mean process output²⁷. If the dataset in question follows a normal distribution, 99.7% of the data points will occur within three standard deviations of the mean value. A normal distribution is a

²⁵ W. KENTON, 'Three-Sigma Limits Definition', 2022. <https://www.investopedia.com/terms/t/three-sigma-limits.asp> (accessed Oct. 01, 2022).

²⁶ B. McNeese, 'Three Sigma Limits and Control Charts', BPI Consulting, 2017. <https://www.spcforexcel.com/knowledge/control-chart-basics/three-sigma-limits-control-charts> (accessed Oct. 01, 2022).

²⁷ C. Berardinelli, 'Control Limits Definition', 2013. <https://www.isixsigma.com/dictionary/control-limits/> (accessed Sep. 23, 2022).

probability distribution that is symmetrical about the mean [41]. This infers that data values in a dataset near the mean value occur more frequently than values much larger or smaller than the mean²⁸. Graphically this appears in the form of a “bell curve” as seen in Figure 11.

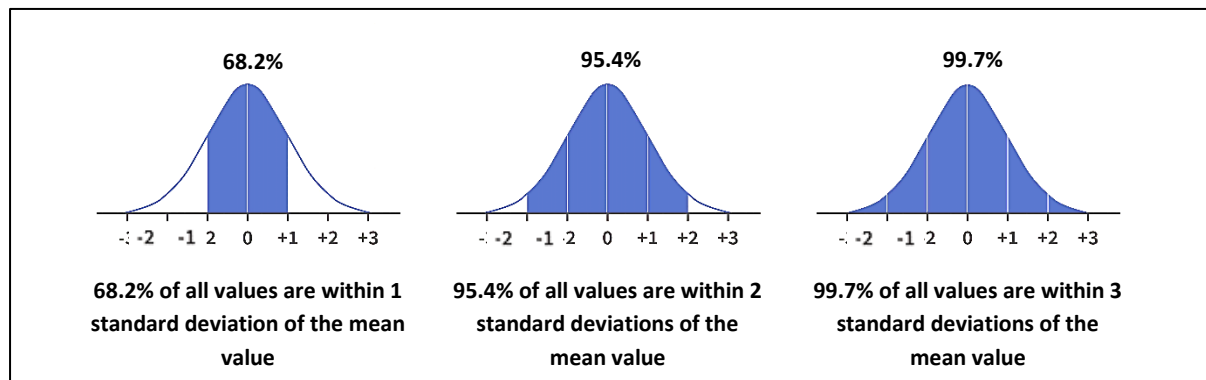


Figure 11: Normal distribution and standard deviations about the mean²⁹

A typical three-sigma control chart consists of three attributes, namely a centre line (CL) which represents the mean value of the dataset, an upper control limit (UCL), and a lower control limit (LCL) [41]. The UCL is three standard deviations above the mean and the LCL is three standard deviations below the mean³⁰ as seen from Figure 12.

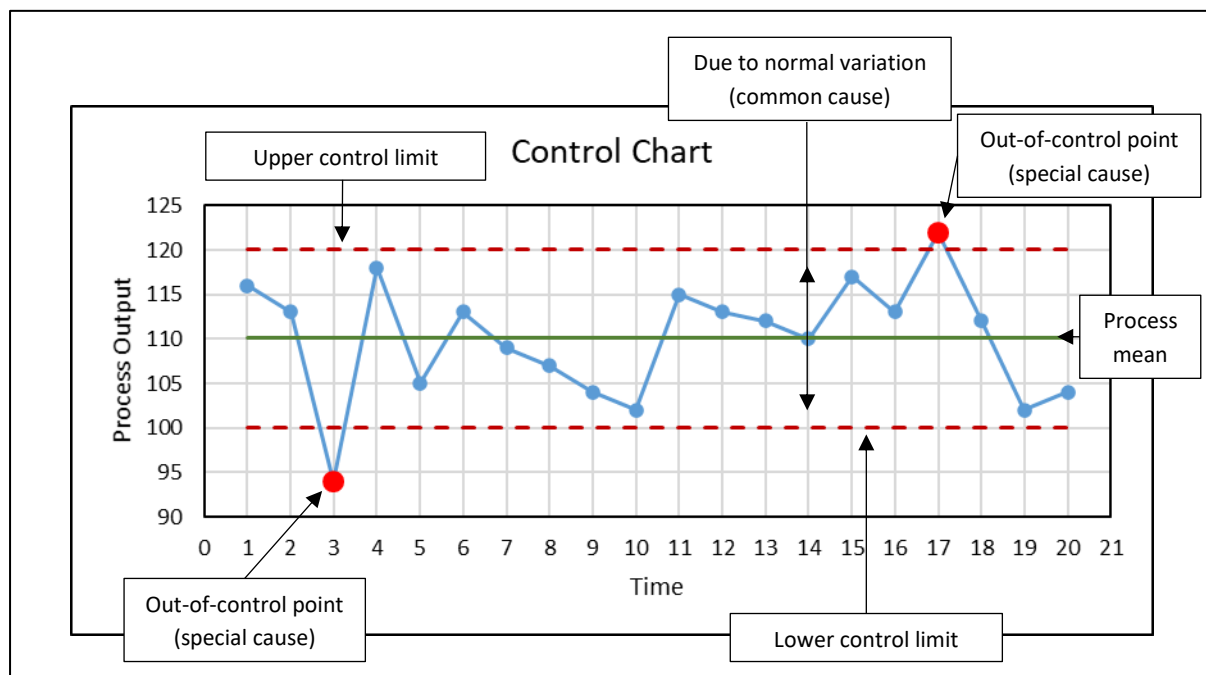


Figure 12: Typical control chart³¹

²⁸ J. CHEN, 'Normal Distribution: What It Is, Properties, Uses, and Formula', 2022. <https://www.investopedia.com/terms/n/normaldistribution.asp> (accessed Oct. 02, 2022).

²⁹ Adapted from: J. CHEN, 'Normal Distribution: What It Is, Properties, Uses, and Formula', 2022. <https://www.investopedia.com/terms/n/normaldistribution.asp> (accessed Oct. 02, 2022).

³⁰ C. Berardinelli, 'Control Limits Definition', 2013. <https://www.isixsigma.com/dictionary/control-limits/> (accessed Sep. 23, 2022).

³¹ Adapted from: A. Foley, 'Control Charts: Everything You Need To Know', 2022. <https://www.clearpointstrategy.com/control-charts-everything-you-need-to-know/> (accessed Oct. 01, 2022).

It is necessary to understand the underlying statistics behind the control chart to fully grasp its function. The process mean may be determined based on a sample of the process dataset (sample mean) or the entire dataset (population mean)³². Let n denote the number of process values in the sample dataset with values of $x_1, x_2, x_3, \dots, x_n$. The sample mean is denoted by $\bar{x}$ and may be calculated using Equation 4 [41]:

Equation 4: Sample mean

$$\bar{x} = \frac{x_1 + x_2 + \dots + x_n}{n}$$

Alternatively, Equation 4 may also be expressed with the Greek capital letter, Σ , which signifies “the sum of”.

Equation 5: Alternative sample mean expression

$$\bar{x} = \frac{\Sigma x}{n}$$

On the other hand, the population mean is expressed using the Greek lower-case letter “mu”, denoted as μ , while the population dataset is denoted by N [41].

Equation 6: Population mean

$$\mu = \frac{\Sigma x}{N}$$

The standard deviation is used to depict the similarity or variance of the data value in a sample or population. It provides an indication of how well the mean value represents the entire dataset. A high standard deviation signals that a large spread of values exists in the dataset and, therefore, indicates a large variation between individual data points. The opposite also holds true with a small standard deviation³³.

Under normal conditions, determining the standard deviation of the population is preferred, as it represents the entire dataset. However, this is not always possible, therefore a sample is used to estimate the population.

³² Lund Research Ltd, 'Mean, Mode and Median - Measures of Central Tendency - When to use with Different Types of Variable and Skewed Distributions', 2018. <https://statistics.laerd.com/statistical-guides/measures-central-tendency-mean-mode-median.php> (accessed Oct. 01, 2022).

³³ Lund Research Ltd, 'Measures of Spread | How and when to use measures of spread', 2018. <https://statistics.laerd.com/statistical-guides/measures-of-spread-absolute-deviation-variance.php> (accessed Oct. 01, 2022).

The sample standard deviation is denoted by s and is formulated by Equation 7 [42]:

Equation 7: Sample standard deviation

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}$$

where $\sum$ signifies “the sum of”, x_i the i^{th} data point in the sample, $\bar{x}$ the sample mean, and n the sample size. In contrast, the standard deviation of the population is denoted by σ and is calculated using Equation 8:

Equation 8: Population standard deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (x_i - \mu)^2}{N}}$$

where $\sum$ signifies “the sum of”, x_i the i^{th} data point in the population, μ the population mean, and N the population size³⁴.

The attributes of the three-sigma control chart can be derived from Equation 4 to Equation 8. When using a sample of the dataset being analysed, the attributes are expressed using Equations 9, 10, and 11 [42]:

Equation 9: Control chart sample CL

$$CL = \bar{x}$$

Equation 10: Control chart sample UCL

$$UCL = \bar{x} + 3s$$

Equation 11: Control chart sample LCL

$$LCL = \bar{x} - 3s$$

³⁴ Lund Research Ltd, ‘Measures of Spread | How and when to use measures of spread’, 2018. <https://statistics.laerd.com/statistical-guides/measures-of-spread-absolute-deviation-variance.php> (accessed Oct. 01, 2022).

When the population is used to analyse the dataset, the attributes are determined using Equations 12, 13, and 14 [42]:

Equation 12: Control chart population CL

$$CL = \mu$$

Equation 13: Control chart population UCL

$$UCL = \mu + 3\sigma$$

Equation 14: Control chart population LCL

$$LCL = \mu - 3\sigma$$

From these equations, the upper and lower boundaries of acceptable process performance are established alongside the process mean output and the control chart can be constructed and implemented to monitor the process output³⁵.

A control chart is a versatile data collection and analysis tool used in various industries. It is considered one of the fundamental quality tools and is a key component of the management reporting process utilised in stock trading algorithms, manufacturing, and process improvement methodologies such as Total Quality Management (TQM) and Six Sigma [39].

A control chart is, therefore, an effective tool for integrating with monitoring and performance reporting tools to continuously monitor and improve power factors. Aside from enabling the monitoring of a process or system, it also serves as an early warning system to facilitate preventative action^{36, 37}. Realistically, personnel cannot continuously monitor a process to identify issues, hence the use of a notifications system should be explored alongside the implementation monitoring and reporting tools. This could notify relevant personnel regarding a potential issue without them having to monitor the performance throughout the day.

1.6.4 Notification system

A notification system is a set of protocols and procedures that generate and distribute messages to individuals or groups of people to inform them of the occurrence of a particular event³⁸. These systems are usually automated to relay information in real-time to relevant stakeholders, particularly when communicating critical information.

³⁵ C. Berardinelli, 'A Guide to Control Charts', 2013. <https://www.isixsigma.com/tools-templates/control-charts/a-guide-to-control-charts/> (accessed Oct. 02, 2022).

³⁶ U. Chitranshi, 'An Ultimate Guide To Control Charts In Six Sigma', 2018. <https://www.greycampus.com/blog/quality-management/an-ultimate-guide-to-control-charts-in-six-sigma> (accessed Sep. 23, 2022).

³⁷ A. Foley, 'Control Charts: Everything You Need To Know', 2022. <https://www.clearpointstrategy.com/control-charts-everything-you-need-to-know/> (accessed Oct. 01, 2022).

³⁸ J. Laukkonen, 'What Is a Notification System?' 2022. <https://www.easytechjunkie.com/what-is-a-notification-system.htm> (accessed Sep. 23, 2022).

There are various means by which a notification can be distributed. The most common communication channels are emails, text messages, phone calls, and mobile applications. Some systems may use multiple channels to relay important information, as this is more likely to be successful in informing personnel than a single notification method³⁹.

Notification tools are incorporated into electrical management systems to improve the management of power quality, such as power factors, on facilities. This is achieved by sending a notification to a user's mobile phone in real-time which, in turn, improves monitoring efficiency and flexibility [43].

In the era of the internet and smartphones, mobile applications have become a common source of notifications⁴⁰. Mobile applications have two types of notifications, namely push notifications and in-application notifications. Push notifications are messages that a user can access without opening the application, while in-application notifications are only visible to the user after the application has been opened. Push notifications are generally used more often than in-application notifications⁴¹.

The implementation of a mobile application with push notifications could assist in alerting personnel regarding poor power factors. A notification can be linked and triggered based on the limits of a control chart that is monitoring the reactive power compensation performance of capacitor banks.

SMS text messages could also be distributed alongside an application's push notifications, as they do not require an internet connection to be transmitted and received by a user⁴². Therefore, they can be used as a backup in the case of remote locations where internet connections may be poor [43].

The implementation of web-based monitoring, reporting, and notification tools can be useful to industrial customers to improve power quality management [44]. South African gold mines are typically located in remote areas. Thus, combining the use of push notifications via a mobile application and SMS technology with PF monitoring and reporting tools may prove to be beneficial towards improving PFM on deep-level mines.

³⁹ C. Duncan, 'Employee Notification System: Keep Your People Informed and Safe', 2022. <https://www.alert-software.com/blog/employee-notification-system> (accessed Oct. 08, 2022).

⁴⁰ J. Low, 'Notification System Architecture. Let's design a notification service.', 2021. <https://medium.com/interviewnoodle/notification-system-architecture-e0d98ab3d18> (accessed Oct. 08, 2022).

⁴¹ A. Khomych, 'Push Notifications vs. In-App Messaging', 2022. <https://blog.getsocial.im/push-notifications-vs-in-app-messaging-what-s-the-difference/> (accessed Sep. 23, 2022).

⁴² K. Wood, 'Can I Still Receive Texts With Cellular Data Off?', 2022. <https://xtrium.com/can-i-still-receive-texts-with-cellular-data-off/> (accessed Oct. 08, 2022).

From the background provided in Sections 1.1 to 1.6, it is evident that PFM is vital in maintaining the stability of South Africa's national electricity grid. Furthermore, it can negatively influence the operational efficiency and operating costs of high-energy users such as deep-level gold mines which are heavily reliant on electricity.

PFM has become a point of contention in recent years with many South African mines neglecting PFM and using dated PFC measures. The following section will explore literature related to PFM to provide insight into the current industry approach and new available technologies.

1.7 Literature review

1.7.1 Overview

The following section investigates the literature related to power factors. Various studies within the fields of PFM and power quality were examined to identify valuable insights that can be used to assist in the development of a strategy that could potentially improve the management of power factors on deep-level gold mines.

1.7.2 Study boundaries

It is evident from the background conducted in Sections 1.2, 1.3, and 1.4 that the mining industry is a major consumer of electricity within South Africa and is faced with many challenges. The average electricity tariff for mining has increased significantly over the last two decades, contributing to electricity costs becoming a major operational expense. Furthermore, poor power factors have a substantial impact on equipment efficiency and a mine operation's electricity bill. PFM is, therefore, instrumental in mitigating the negative effects of high reactive energy on deep-level gold mines. An investigation was done to establish the current industry approach regarding PFM and the latest technologies being used.

The research databases that were considered included IEEE Xplore, ScienceDirect, Scopus, Elsevier, Academia.edu, Journal of Energy in South Africa, and Google Scholar. The foundation of this literature study was based on keywords and phrases such as "power factor management", "power factor correction", "power factor monitoring", "power factor reporting", "power factor ranking and prioritisation", "power quality management", and "power quality monitoring".

Keywords were identified through the background study to analyse the available literature related to power factors. Additionally, questions pertaining to each keyword were asked to establish whether a study could provide relevant insights. These questions are as follows:

- Power factor management – Did the study examine and implement a power factor management strategy?
- Monitoring – Did the study develop and implement data monitoring tools?
- Performance reporting – Did the study incorporate performance reporting?
- Ranking and prioritisation – Did the study include the ranking and prioritisation of various facilities?
- PFC – Did the study investigate PFC?
- Web-based tools – Did the study implement a web-based tool for PF monitoring and analysis?
- Notifications – Did the study explore the use of notifications to warn users of poor power factors?
- Mining – Did the study examine power factors within the mining industry?

All literature studies considered were assessed based on the keywords and their associated questions.

1.7.3 Previous research

A summary of each literature study is presented alongside its results and the valuable insights that were derived from the keywords and criteria questions established in Section 1.7.2. The shortcomings of each literature study are outlined in the state of the art matrix in Table 2.

The research focused on literature published after the year 2012. However, studies published before 2012 that proved to be relevant and contained valuable insight were also considered.

In total, 23 literature studies were considered. Figure 13 provides an overview of the distribution pertaining to the identified literature studies based on the criteria stated above. The majority of the studies reviewed were conference proceedings and journal articles as well as one thesis and one dissertation.

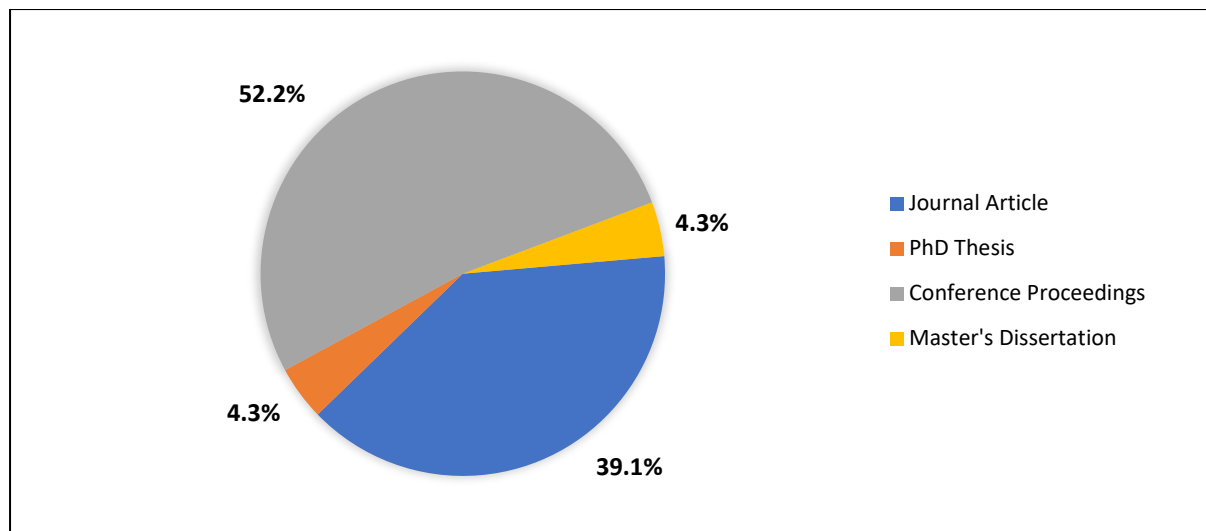


Figure 13: Distribution of literature studies considered

The year range distribution of the literature studies considered are presented in Figure 14.

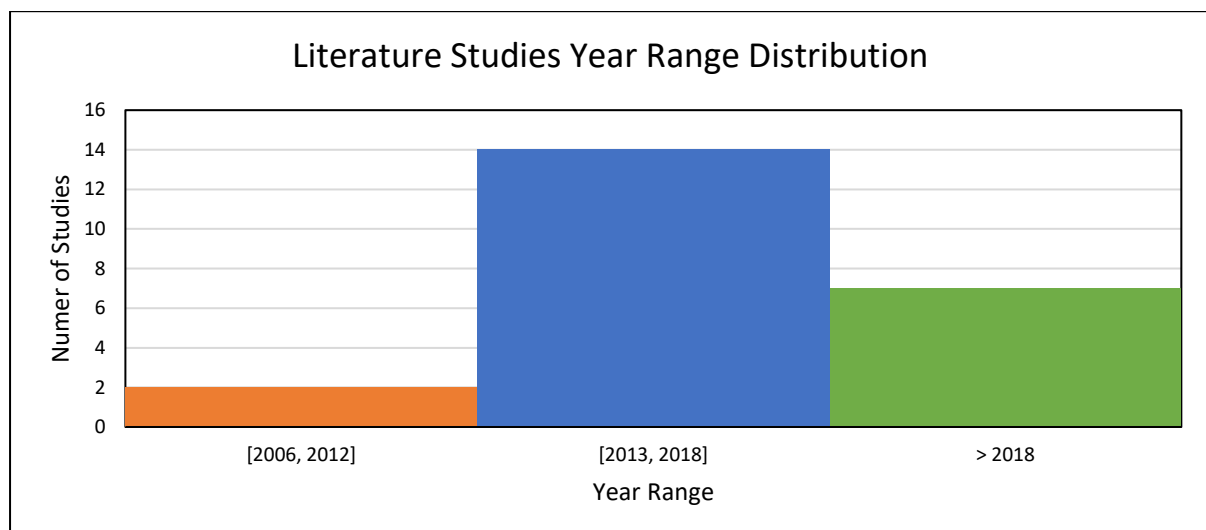


Figure 14: Year range distribution of literature studies considered

The distribution presented in Figure 14 indicates that most of the studies considered were published from 2013 onwards. Only two studies were published between 2006 to 2012, whilst 14 studies were within the range of 2013 to 2018 and 7 of the studies were published after 2018. These studies will now be reviewed.

Study 1: Routray (2015) [12]*Summary:*

Routray developed and tested an automatic power factor correction (APFC) device that controls the number of capacitors utilised to improve a system's PF. The device was built as a basis towards developing and implementing APFC in mines. The study also examined the potential economic benefits of implementing such a device in the electrical system of a coal mine in India.

Results/insights:

The author selected an 89S52 microcontroller as the core from which the APFC device was developed. An algorithm was created to control the number of active capacitors based on the system performance and the desired PF. The connected system's voltage and current readings are sampled and used as input to establish the present PF. The device compares this to the specified PF from the power utility and switches on capacitor banks to compensate for the excess reactive energy accordingly.

The device was tested on three different load types to determine its effectiveness. The results indicated a 9% to 19% improvement in PF depending on the load combinations and a reduction of 1.7% in the total energy consumption. The economic impact analysis concluded that the implementation of such a device would lead to a significant reduction in energy costs. Additionally, the payback period of the case study mine was estimated at around 9 months.

Study 2: Roos et al. (2019) [45]*Summary:*

This case study examined the PFC, load flow, harmonic frequency scans and harmonic voltage distortion analyses of the Grootegeluk mine located in South Africa. The study focused on designing a reactive power and harmonic compensation strategy that would best suit the harsh mining environments and maximise electricity savings. The DlgSilent PowerFactory software was utilised to simulate network conditions and derive the optimal solution.

Results/insights:

This study examined various harmonic and reactive power techniques to develop the optimal solution for the case study mine. The techniques were compared based on filter-type evolution and technology advancement in terms of cost-effectiveness and performance criteria.

The study identified that hybrid and passive filters were more advantageous in terms of compensating for harmonic distortion and reactive power present in large non-linear loads. The solution comprised switched PFC filter banks that were tuned at the fifth harmonic order and designed with future expansion in mind. This resulted in an improved PF of above 0.96 which led to a reduction in energy costs.

The author concluded that this solution can be incorporated throughout the mining industry and can be used as a benchmark in terms of reducing energy costs on the Eskom electricity bill. Furthermore, the implementation of a PF report was recommended for future work to assist in maintaining and continuously improving the PF.

Study 3: Wahab et al. (2021) [46]

Summary:

This study focused on examining the importance of PFC and analysing economic improvement following its application. The case study was based on the implementation of PFC of 9 machines at a factory in the south of Lebanon utilising a capacitor bank. The objective was to raise the PF close to unity to reduce the monthly demand kVA charges on the electricity bill as well as penalties for poor PF. The size of the capacitor bank was determined based on the power demand of the machinery.

Results/insights:

The proposed implementation of the capacitor bank solution would raise the PF of the factory from 0.8 to 0.9, resulting in a 15% reduction in electricity costs over a period of 4 years. This cost reduction includes the investment costs, the annual maintenance costs, yearly upgrade costs due to expansion as well as the depreciation cost associated with the capacitor bank's life cycle of 12 years. The author concluded that the reduction in electricity costs via PFC can be effectively realised and is economically viable, emphasising the importance of incorporating PFC and its impact on the consumer's electricity bill.

Study 4: Ortega et al. (2019) [47]

Summary:

This study focused on developing an algorithm to optimise PF compensation using a cloud-based monitoring system. The teaching-learning-based-optimisation algorithm was adapted to determine the optimal capacitor combination required to improve the PF of a system based on various power-related measurements.

An Arduino microcontroller was used to run the algorithm and input data for the algorithm was acquired via sensors. The calculations were stored on Google Sheets using a cloud data logger to monitor and analyse the optimal PF compensation and determine which capacitors were connected in real time. Furthermore, an Android application was developed to monitor the data on Google Sheets in real time via a smartphone or tablet.

Results/insights:

This study provided insight into the use of algorithms for PF improvement and concluded that the cloud-based analysis and monitoring system was effective in optimising power factors. Furthermore, combined with an Android application, enabled remote data visualisation and analysis. This emphasises the necessity for remote PF data monitoring to allow decision-making that will assist in managing PF performance. The study concluded that such a system has the potential to significantly impact economic savings.

Study 5: Nguyen et al. (2018) [48]

Summary:

This study conducted an economic analysis of using behind-the-meter (BTM) energy storage systems (ESS) for electricity TOU bill management combined with PFC. The author determined the optimal ESS charge/discharge operating scheme that minimises the energy and demand charges on the electricity bill while correcting the PF of the waste treatment plant in New Mexico. This study aimed to propose an approach that would maximise the economic benefit of BTM ESS for TOU management while providing PFC.

Results/insights:

Previous research conducted by the author indicated that the potential benefit of implementing BTM ESS for reactive power applications has yet to be explored. The implemented solution utilised an inverter to inject or absorb reactive power while transferring real power to charge or discharge the ESS. It was established that this type of application was enabled by recent improvements in electronic technologies.

The results indicated that an ESS can significantly reduce the electricity cost by reducing the power consumption during peak electricity tariff periods. The proposed method of utilising the inverter successfully charged and discharged the energy storage for TOU management while also maintaining a PF above 0.9.

The author concluded that such an approach is best suited for large commercial or industrial consumers. Furthermore, the benefit of this approach is magnified when incorporated into a system that has large amounts of photovoltaic (PV) technologies (solar panels) installed.

Therefore, the implementation of such an approach combined with capacitor banks should be investigated within the mining industry. This also showcases the need to monitor power consumption and power factors to facilitate the development and implementation of new energy-saving strategies.

Study 6: Herath (2008) [49]

Summary:

This study set out to develop and present new power quality data management guidelines and reporting methodologies alongside several other novel contributions. These methodologies were developed to provide valuable feedback to end users, utilities, and regulators to allow for the assessment of equipment operability. This enables the comparison of competitive distributor performance.

Results/insights:

The power quality reporting methodology suggests a short-term, medium-term, and long-term reporting structure for power quality analysis. This reporting approach can be consulted for the development of a daily PF performance report. The methodologies developed in this study were applied to several Australian public utilities to demonstrate their ability to rank various sites for power quality improvement and to develop a power quality benchmark based on the ranking of these utilities.

The author concluded that the implementation of these guidelines and methodologies is necessary for effective management of power quality to reduce the performance impact on end-user equipment. This showcases the viability of investigating the use of performance reporting alongside the ranking and prioritisation of mine operations based on PF performance to effectively improve PFM. The author also identified that further investigation is required into automated data management, reporting, and analysis systems. This suggestion by the author will be considered with regards to the development and implementation of reporting and monitoring tools to potentially improve the PFM on deep-level mines.

Study 7: New et al. (2019) [50]*Summary:*

In this study, a real-time energy monitoring and reporting tool was developed for the Hal Marcus College of Science and Engineering building of the University of West Florida (UWF). This allows the university to record the power quality and energy consumption in real-time, review historic data, and identify patterns that can be utilised to manage the power quality and energy usage.

Results/insights:

The software developed in this project displays data in graphical and tabular outputs based on user input. The reporting and visualisation software was developed using Python.

The main benefits of these monitoring and reporting tools were high-accuracy readings and the ability to monitor power profiles to analyse patterns and potential issues, enabling the identification of opportunities for improving cost and efficiency.

Study 8: Biswas et al. (2015) [51]*Summary:*

This study developed an automatic power quality improvement system that continuously monitors the PF load to inject capacitance when the PF falls below a specified level.

Results/insights:

A microcontroller was used as the basis for the system that executed an algorithm developed to determine the required capacitance to be injected based on the input PF load. The author concluded that this method reduces the capacitance switching occurrences versus previous work where capacitors were injected one at a time until the desired PF was reached. Therefore, capacitor switching losses were overcome with the implemented technique. This study once again showcases the need to monitor power factors to enable solutions that will improve the management of poor power factors.

Study 9: Khanchi et al. (2013) [52]*Summary:*

This study focused on improving the PF of an induction motor by using a capacitor bank. The main objective was to develop and implement an energy-saving strategy for an industrial distribution network. The author noted that this can be achieved by improving the efficiency at which the electric load operates and decreasing the network losses. The developed strategy improves the PF of a network by installing shunt capacitors at optimal size and location based on network analysis.

Results/insights:

This study noted the extensive use of induction motors due to their low cost, reliability, and robustness; hence they are utilised to power most machines for industrial and mining applications. It has also been estimated that these motors are responsible for 70% to 80% of all electricity consumed in the world, illustrating the need for PFC and the importance of PFM to mitigate poor power quality.

A simulation was used to determine the required capacitance to improve a network's PF. The analysis indicated that the PF of an induction motor is the highest when at full load (0.84) and the lowest at no load (0.17) but can be improved from 0.84 to 0.95 at full load with PFC.

The study concluded that PFC could reduce electricity costs and may assist in reducing network expansion costs. Furthermore, capacitor banks can be installed on a timely basis and are not subject to environmental factors such as weather and shading.

Study 10: Adefarati et al. (2013) [53]*Summary:*

This study investigates the economic and industrial application of PF improvement via capacitors. The author used computer software to analyse the total cost associated with PFC and the expected annual electricity savings when implemented.

The objectives of the research conducted were: (1) To formulate a mathematical model that optimises the cost of electricity in the industrial sector via the application of PF improvement. (2) To estimate the annual power output of a power plant, and (3) the annual consumer power consumption. (4) To develop approaches that will assist utility companies to improve power factors, and (5) determine the impact of implementing reactive charge penalties to discourage

poor power factors. (6) To propose a computational approach to PF improvement in the industrial sector that will (7) reduce power losses (8) and improve voltage drop. (9) Lastly, to investigate the relationship between current reduction and the sizing of cables and a reduction in expansion costs.

Results/insights:

This study indicated the importance of power systems with various equipment such as alternators, switchgears, transformers, and transmissions to achieve a PF close to unity to provide optimal conditions from an engineering and economic perspective. It was concluded that power systems should operate at a PF between 0.8 and 1 to ensure good performance. This reduces the monthly electricity costs, is economically viable, improves voltage drop, plant efficiency and reliability, and reduces power losses and expansion costs.

Study 11: Pachanapan (2019) [54]

Summary:

The purpose of this study was to design a controller that controls the reactive power supplied by a PV rooftop system. The objective of this controller is to manage the PF at the electricity POD to reduce PF penalties for commercial consumers with large grid-tied PV systems installed. The DIgSILENT PowerFactory software is used to simulate the performance of the proposed control system over 24 hours.

Results/insights:

The need for this study was derived from the recent upsurge across the world to install large-scale grid-tied PV rooftop systems on commercial buildings to reduce electricity costs. However, the standard PV system only reduces the active power consumption in the system but leaves the reactive power unchanged, therefore, reducing the overall PF. This may result in the PF falling below the prescribed limit of the power utility which, in turn, may lead to penalties on the monthly electricity bill.

The smart control algorithm developed in this study analyses the PF at the POD and utilises the PV interfaced-inverter and -converter to supply suitable active power and reactive power. The PV grid-tied converter will automatically inject the required reactive power compensation into the grid when the PF at the POD has reached the prescribed lower limit of the power utility. The simulation results indicated that this proposed method can actively manage dynamic power factors while the PV system operates. Further investigation regarding this research should be considered for future implementation in the mining industry.

Study 12: Saha et al. (2013) [55]*Summary:*

This study constructed a compact and energy-efficient system to monitor and automatically control power factors based on a microcontroller kit with a zero-crossing detector- and relay driver-circuit. The input data is gathered and analysed in real-time to inject the available capacitance into the system until the desired PF is achieved. The goal of this study was to develop a system that could monitor and improve the PF for any connected load.

Results/insights:

The author successfully developed a prototype system to monitor and control the PF of a connected system. The system was tested on various loads where the PF was accurately displayed and corrected close to unity. The author concluded that such a system may be particularly useful in industries with high reactive energy consumption. Furthermore, improved power management can be achieved by logging the power and PF data and transmitting it to remote users for further analysis. Alert messages should also be considered to notify users when a set PF limit has been reached. This will be explored further when addressing the development of a solution.

Study 13: Maheepala et al. (2018) [56]*Summary:*

The authors of this study designed an energy monitoring, analysis, and solution-providing system for energy auditing. The objective of an energy auditing system is to examine and analyse the flow of energy to reduce its consumption without negatively impacting production quality and quantity. Energy auditing is described as the first step in the identification process to recognise savings opportunities in residential and commercial applications. This has become an important task in the industrial sector due to increasing energy costs.

The proposed system mainly consists of real-time data monitoring, data analysis, real-time data plotting based on user requirements, problem identification, remote accessibility, and technical suggestions regarding PFC and load shifting for demand-side-management (DSM). Furthermore, warnings for emergencies were also incorporated into the system.

Results/insights:

The proposed model can be categorised into five main sections:

1. Data acquisition and transferring.
2. Communication protocol.
3. Data storing and processing.
4. Web-application development and report generation.
5. Emergency detection.

Figure 15 illustrates the high-level architecture of the proposed system.

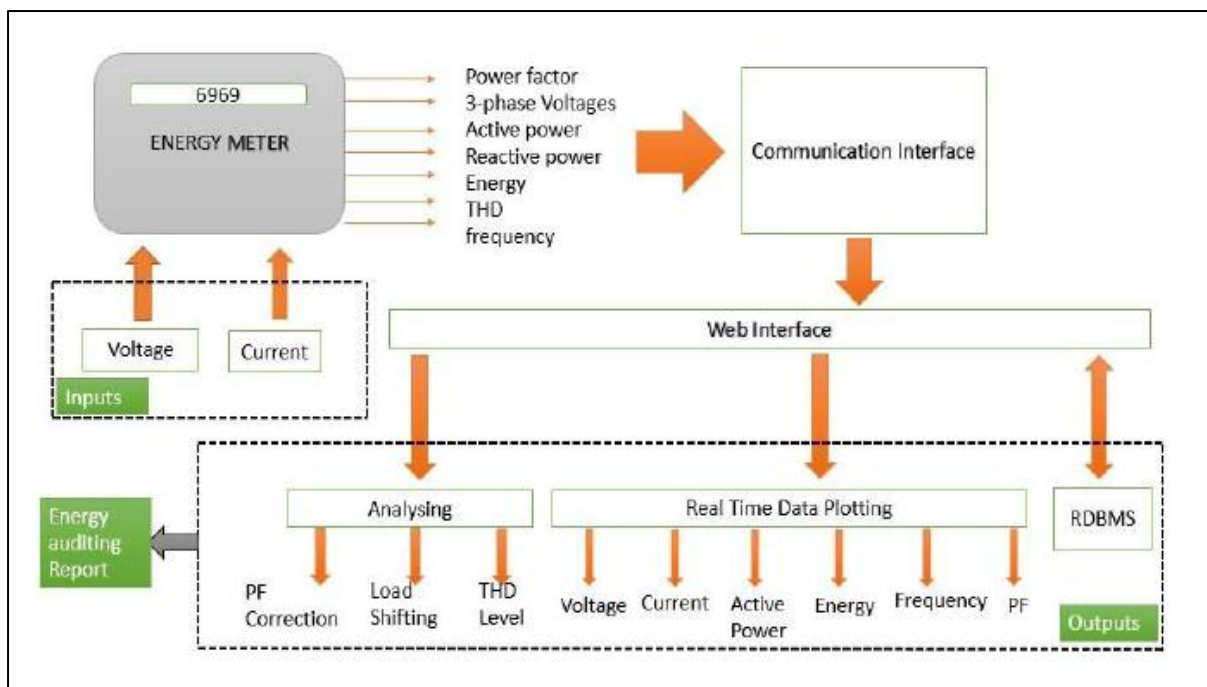


Figure 15: High-level system architecture [56]

(1) Phase voltages and line currents are used as the base data inputs of the system via a three-phase energy meter. The meter then supplies the system with the voltage, current, active power, reactive power, PF, and frequency. **(2)** The data is then converted from analog to digital and transferred to a computer where it is stored in the form of a text file in the CSV format.

(3) The text file data is then transmitted and stored in a MySQL database on a web server by using TCP/IP communication protocol (Transmission Control Protocol/Internet Protocol). The database is updated every second allowing the web application to provide real-time monitoring of energy data. Once the data has been collected (at least three days), the analysing phase is initiated. This section is focused on examining the data to provide solutions for low PF and

peak energy time usage. These analysis results are presented to the consumer via the web application.

(4) The primary objectives considered for the development of the web application were remote accessibility, user-friendly interface, availability, and reliability. The web application provides users with features such as real-time energy monitoring, energy savings facilities, and reporting. The reporting section includes the calculated results and energy management suggestions as well as other relevant data. The report is presented to the user in the form of a PDF file. **(5)** An additional feature presented to the user is an emergency notification. This feature is focused on detecting faults and emergencies to inform users via an SMS.

The experimental results indicate that the proposed system can improve energy management for industrial and residential applications. The author concluded that this product improves the efficiency of energy auditing for the user, as it facilitates data analysis and decision-making and provides energy management optimisation proposals.

This study contains valuable insight in terms of its methodology, system architecture, and features; therefore, the methodology and features will be explored for the development of monitoring, reporting, and notification tools to improve the management of power factors on deep-level mines.

Study 14: Longo et al. (2018) [57]

Summary:

This study aimed to analyse the energy consumption of a railway station building to identify potential energy efficiency improvement opportunities. This was achieved by implementing a two-step approach:

- Data collection from the POD and subsequent analysis, and
- installation of a monitoring system as well as subsequent data collection and analysis.

Results/insights:

The monitoring system installed stored data on a data logger for extraction to a personal computer. The data gathered comprised three-phase and single-phase voltage and current, real and reactive power, and PF and frequency.

The author categorised the energy data based on seasonality and the three energy consumption bands (off-peak, standard, and peak electricity usage). It was concluded that the main energy inefficiency was the reactive power consumption, especially during the winter months, which led to an increase in the monthly electricity bill. The importance of improving the efficiency of PFC from the capacitor banks was emphasised.

Furthermore, the study suggests the monitoring and analysis of reactive power absorption from the various loads in the station building. This suggestion will be considered during the development of the PF monitoring and analysis tools. Therefore, incomers on the deep-level mines will also be explored in terms of monitoring and analysis, which could assist in identifying the problem area which resulted in reduced PF performance at a POD.

Study 15: Gu et al. (2013) [58]

Summary:

This paper implements a power monitoring and management system combined with a solar cell that is used to reduce the power consumption of household appliances. The aim of this study was to improve overall energy consumption by reducing wastage within the connected system. The implemented system can monitor the power consumption of all the connected devices within the household and analyse their consumption to enable effective power management. The system consists of a power meter, Zigbee device, and a digital information platform.

Results/insights:

The author developed a power meter to collect the network's power which is then transmitted to the digital information platform via the Zigbee device. A database was constructed and used to store and categorise the power data to determine the state of the connected household appliances. The database includes the measured voltage, power, PF, frequency, and capture time. The user can observe the data via the information platform or use the developed mobile application to remotely monitor the power consumption.

The implemented system enables the user to establish which node in the network has excess power consumption and allows the user to control the power switch of the node (turn on or off). The author concluded that this monitoring system allows effective management of energy consumption within a household to reduce wastage, hence reducing overall energy costs and carbon footprint.

Study 16: Coman et al. (2020) [59]*Summary:*

This study presents a general overview of the influence that PF has on a network and the authors designed a device for PFC. The proposed device makes use of the advances in information technology and communication technology (ICT) to create a new approach for telemetry and remote configuration of capacitor banks. This approach provides flexibility as it can be adapted to many loads depending on the targeted implementation.

Results/insights:

The implemented system utilised a web-based PF application that was developed using the Python coding language. The main advantage of the developed system was its ability to be configured and programmed remotely via an internet connection. This reduced the difficulty of modifying the parameters of the applied algorithm to assist in improving the PF based on the time feedback and artificial intelligence.

The results showed that the PF of the case study improved from 0.64 to 0.8. However, this outcome was not an improvement on other existing methods in terms of PFC. Nevertheless, the implemented system showcased its ability to utilise telemetry to identify potential problems and improve the PF. Furthermore, the energy losses measured due to poor PF were reduced by 20%. The study concluded that PFM is crucial from an economic standpoint, as it reduces penalties on the monthly electricity bill and mitigates equipment efficiency losses.

Study 17: Zheng et al. (2017) [60]

This study presents an in-depth assessment of the technical and economic impact of PFC implementation. The process is verified by analysis of a real-world electrical system and loads. Furthermore, the authors demonstrate the efficiency of the method used to determine the ideal location and size of a capacitor bank installation to attain the desired PF.

Results/insights:

This research paper presents a case study on the long-term impact of PFC on the industrial load. The case study is based on a site with a poor PF and high peak demand. Through the implementation of the capacitor bank installation, the average PF was improved from 0.87 to 0.98 and the maximum demand (kW and kVA) was reduced. The resulting benefit equated to a \$6 000 reduction in the annual demand charges.

The authors stated that the analysis of the energy usage profile is important when studying a site's consumption patterns and recommend that the energy data should form part of the initial data collection process. Additionally, a DSM strategy is advised to mitigate sudden increases in power consumption that may cause issues with fixed PFC such as with capacitor banks. Moreover, equipment maintenance is crucial to ensure that equipment does not consume more power than it should. Therefore, a PF monitoring system that additionally monitors the power consumption could potentially assist with identifying equipment inefficiencies over time and facilitate a DSM program.

Study 18: Morales-Velazquez et al. (2017) [61]

Summary:

This research paper presents a smart sensor network to monitor an electrical system's power quality. The proposed system is capable of real-time and offline data processing. The system was tested on a residential home, public building, and industrial site.

Results/insights:

The research outlines that smart meters form part of the basis of the future smart grid as they allow for remote monitoring across the various points of the grid and provides real-time monitoring and failure detection. The developed smart sensor network computes power quality measurements such as the PF and total harmonic distortion and detects a disturbance in the network. The system utilised a mobile device such as a smartphone or tablet to integrate the smart sensor network, allowing for the synchronisation of the smart sensor and remote monitoring. The author concludes that this is a powerful tool to inspect an electrical system in a non-intrusive way.

Study 19: Kabir et al. (2017) [62]

Summary:

This study set out to develop a PFC unit that can monitor the energy consumption of a system and automatically improve the PF. The basis of the proposed system is a pre-programmed microcontroller and the implementation of an open-source energy monitoring library called Emonlib.

Results/insights:

The technical design of the proposed system comprises four main steps, namely (1) Emonlib inclusion, (2) calibration of Emonlib, (3) reactive power calculation, (4) and capacitor switching.

Emonlib is an open-source energy monitoring library that can read analog voltage and current signals. Furthermore, it calculates the main voltage, main current, real power, apparent power, reactive power, and PF. The pre-programmed microcontroller calculates the required reactive power compensation via the measured power parameters to raise the PF to an acceptable range, which automatically switches the capacitors from the capacitor bank into the network and provides real-time monitoring of the power parameters.

The author concluded that this PFC technique can be used to improve the stability and efficiency of systems in the industrial sector, commercial lines, and power distribution systems. Moreover, the system can assist in reducing the monthly energy charges on the utility bill and ultimately lower the greenhouse gas emissions and fossil fuel depletion of power stations due to the reduced power consumption.

Study 20: Rahman et al. (2020) [63]*Summary:*

This study developed an automatic PFC system via capacitor banks. The system uses a microcontroller to calculate the required capacitance to improve the PF and then switches on a capacitor accordingly. The PF can also be wirelessly monitored on a computer via radio frequency (RF).

Results/insights:

The Proteus Design Suite simulation software was used to assist in the design of the proposed PFC system and monitoring software was developed using Visual Studio. The developed system can handle a load of 1 kW and continuously monitors the PF. The system takes the voltage and current as its inputs to determine the current PF and whether there is a phase difference between the two inputs. If there is, it will establish whether this phase difference is leading or lagging.

The following procedures will then be executed based on the identified state (leading or lagging):

1. If lagging (PF between 0 and 1): The system will turn on the capacitor bank.
2. If leading (PF between -1 and 0): The system will turn off the capacitor bank.
3. If there is no phase difference: The system will indicate a unity PF on the connected display.

The author concluded that the system can successfully improve the PF of the connected load and assist in reducing equipment damage due to low PF. Furthermore, the implementation of such a system would be useful in the industrial sector with high inductive loads. The author also suggested utilising the internet protocol instead of RF technology to enable monitoring and control over the internet from anywhere in the world. The implementation of a web-based tool will, therefore, be explored.

Study 21: Bayhan et al. (2013) [64]

Summary:

This study introduced an internet-based power quality monitoring system. The system utilises a handmade measurement board to measure the input voltage and current from a distribution panel. These input values are then transmitted to a computer via a data acquisition board where the obtained data is then analysed to establish the power quality.

Results/insights:

The author developed the data analysis software utilised by the system via the LabVIEW programming language. This analysis software comprises three main functions: voltage analysis, current analysis, and power analysis. The system is capable of monitoring power quality disturbances such as harmonic distortion, voltage swell and sag, instantaneous power, average power, and interruptions. Additionally, the developed monitoring platform was published online via the LabVIEW web publishing tool, which allows the user to remotely access the tool via a web browser for real-time monitoring and control.

From the experimental results, it was concluded that the proposed system was successfully implemented and fulfilled the objective of providing power quality monitoring via a web browser. Furthermore, the author concluded that the developed prototype is cost-effective and forms a suitable base for further development of power quality and energy monitoring systems that can be utilised in the industrial and commercial sectors.

Study 22: Kulkarni et al. (2015) [65]*Summary:*

The aim of this study was to develop an intelligent PFC method based on the use of a programmable logic controller (PLC) as a control system. The study focused on the improvement of the industrial PF, as it is necessary for optimal operation and assists in minimising the energy penalties on the electricity bill due to low PF. This involves measuring the PF from the supply line via a power meter and utilising a PLC program to calculate and activate capacitor banks of the required rating to compensate for the measured reactive power. The case study presented in this paper is based on the implementation of the proposed method in a real industrial facility.

Results/insights:

A ten-step control algorithm was developed using the ladder programming technique which was designed based on the conditions of the case study facility. The results of the control algorithm were simulated using the TWIDOSUITE PLC simulation package while the Invensys Wonderware 'Intouch' SCADA simulator was used to simulate the impact on the case study system. The realised system improvements were reduced operating time and manpower and achieving the optimal PF for facility operation.

The author concluded that the proposed system has various applications in several fields such as control system design, energy-saving solutions, and plant management. Additionally, the implementation of the proposed system can make static shunt capacitors behave as if they were a dynamic source of PFC through automatic switching. The system can also be installed at the reactive loads or the service end.

Study 23: Colak et al. (2006) [66]*Summary:*

This study presents a novel technique to correct the line PF with variable loads based on artificial neural networks (ANNs) where a synchronous motor is controlled to manage the reactive power of the system. The ANN compensator was trained with the extended delta-bar-delta learning algorithm and inserted into a microcontroller to achieve more effective and efficient reactive power compensation.

Results/insights:

Artificial neural networks (ANN) are a biologically inspired optimisation technique that consists of numerous processing elements, representing neurons in a brain, that are highly interconnected in various layers. These “neurons” process information based on the external inputs the network receives. It can learn patterns by being trained with several known patterns where weights and thresholds are used to adjust the learning process. The ANN is deemed as sufficiently trained or optimised once there is minimal difference between the ANN’s output and the target output.

The proposed system continuously monitors the PF and determines the field current required to control the synchronous motor to improve the PF. The results presented indicate that the proposed technique overcomes the problems that occur in conventional compensation methods such as time delay, step changes of reactive power, under compensation, voltage drop, and harmonic distortion, providing an accurate, rapid, and low-cost compensation approach.

The author concluded that this technique may be especially appealing for industrial applications, as the synchronous motor can be utilised in the system for other purposes than reactive power compensation. The main disadvantages identified were the requirement for a synchronous motor, selecting appropriate patterns to train the ANN in an offline process and then inserting it into the microcontroller.

1.7.4 State of the art matrix summary

A summary of the literature reviewed in Section 1.7.3 is presented in the state of the art matrix in Table 2. These studies were deemed the most appropriate regarding the study boundary outlined in Section 1.7.2. Criteria that are satisfied by the study are highlighted in green, while the shortcomings are indicated in red.

From the literature evaluated, it is evident that the majority of the studies focused on the implementation of monitoring tools as part of their PFM approach. However, only [47], [56], [58], [59], and [64] made use of web-based tools only [47] and [61] employed smartphone integration. Hardly any focus was placed on the implementation of a notification system to extend the reach of PF monitoring tools. [56] incorporated emergency notifications via SMS and [55] recommended the use thereof.

As seen from the state of the art matrix, the vast majority of the studies neglected the use of performance reporting except for [49], [50] and [56], whilst only [49] made use of ranking and

prioritisation related to PF/power quality. Additionally, only studies [12] and [45] explored power factors within the mining industry.

From Table 2 it can be seen that there is a lack of research pertaining to PFM within the mining industry. Considering the heavy reliance of deep-level mines on electricity and the negative impact poor power factors can have on energy costs, the topic should be further investigated. This combined with the adverse effects of poor PFM, especially from large energy consumers, on the electrical grid substantiates the need for this study.

Table 2: State of the art matrix

Reference	Date	Power factor management	Monitoring	Performance reporting	Ranking and prioritisation	Power factor correction	Web-based tools	Notifications	Mining	Title
Routray [12]	2015									Microcontroller based automatic power factor correction in mines
Roos et al. [45]	2019									Reactive power and harmonic compensation: A case study for the coal-mining industry
Wahab et al. [46]	2021									Economic improvement of power factor correction: A case study
Ortega et al. [47]	2019									Power factor compensation using teaching learning based optimization and monitoring system by cloud data logger
Nguyen et al. [48]	2018									Optimal time-of-use management with power factor correction using behind-the-meter energy storage systems
Herath [49]	2008									Power quality data management and reporting methodologies
New et al. [50]	2019									Design and implementation of a real-time energy monitoring and reporting system
Biswas et al. [51]	2015									Automatic power factor improvement using microcontroller
Khanchi et al. [52]	2013									Power factor improvement of induction motor by using capacitors
Adefarati et al. [53]	2013									Economic and industrial application of power factor improvement
Pachanapan [54]	2019									The control of large scale grid-tied photovoltaic rooftop systems to avoid the power factor charge
Saha et al. [55]	2013									ARM(R) microcontroller based automatic power factor monitoring and control system
Maheepala et al. [56]	2018									Designing an energy monitoring, analysing and solution providing system for energy auditing
Longo et al. [57]	2018									Smart energy management of a railway station
Gu et al. [58]	2013									The power monitor system combined green energy
Coman et al. [59]	2020									Improving the efficiency and sustainability of power systems using distributed power factor correction methods
Zheng et al. [60]	2017									Long term effect of power factor correction on the industrial load: A case study
Morales-Velazquez et al. [61]	2017									Smart sensor network for power quality monitoring in electrical installations
Kabir et al. [62]	2017									Automated power factor correction and energy monitoring system
Rahman et al. [63]	2020									Power factor controlling and monitoring wirelessly through computer
Bayhan et al. [64]	2013									Internet based power quality monitoring system
Kulkarni et al. [65]	2015									PLC based intelligent power factor correctors for industrial power systems: A case study
Colak et al. [66]	2006									Power factor correction technique based on artificial neural networks

1.8 Problem statement

From the background gathered on the South African gold mining industry, it was concluded that the industry is confronted with various obstacles that have adverse effects on their profitability and productivity. One of the main challenges is escalating electricity prices due to a deep-level gold mine's intensive use of this resource to perform daily operations. The average electricity tariff has increased significantly over the past two decades which has contributed to it becoming a major operational expense.

Numerous large mining operations have outdated PFC equipment. A significant portion of this equipment is out of commission due to lack of maintenance or has been rendered inadequate due to the expansion of the electrical network. This combined with neglected PFM has resulted in a deterioration in PF performance and increased energy usage.

Poor PFM places additional strain on the electrical infrastructure. As a result, electricity suppliers such as Eskom have implemented penalties by means of reactive energy charges to discourage power wastage during the high-demand season. This increases the electricity costs of large mining operations with outdated PFC equipment and poor PFM.

From previous literature, as summarised by the state of the art matrix in Table 2, it is clear that there is a need to explore the development of PFM tools that incorporate web-based monitoring and reporting as well as notifications on deep-level mines.

1.9 Objectives

The challenges outlined in Section 1.8 emphasise the importance of load management, particularly the reduction of excess reactive energy to reduce electricity costs and avoid negatively affecting operational efficiency of deep-level mines. It is, therefore, important to explore opportunities to improve PFM on deep-level mines that are economical and simple to implement within the available infrastructure.

The study will therefore aim to develop monitoring and reporting tools that have the potential to improve PFM on deep-level mines with existing PFC equipment.

The study objectives are summarised as follows:

- I. Establish the PF performance of various deep-level mine operation PODs.
- II. Rank and prioritise deep-level mine operation PODs for PF improvement based on power factors, demand charges, and reactive charges.
- III. Develop and implement PF monitoring, reporting, and notification tools:
 - a. Web-based monitoring and data visualisation of power factors.
 - b. Daily performance report on historic PF performance.
 - c. Notification system to warn personnel of poor power factors.
- IV. Develop and implement the tools by utilising existing platforms available to the deep-level mine operations.
- V. Reduce capacitor bank downtime by means of earlier fault detection.
- VI. Reduce annual penalties on reactive energy charges and demand charges.

The findings of the study will provide insight into the current PF situation on deep-level mine operations and assist in identifying opportunities for further improvement in terms of PFM.

1.10 System development methodologies

1.10.1 SDLC process models

The SDLC process model is a system development methodology that provides a structured approach for developing a system⁴³. Over the years, various SDLC methodologies have been developed, each with its unique approach to guide the processes involved. These include the Waterfall, Agile, Iterative, V-Model, Spiral, Incremental, DevOps, and RAD (Rapid Application Development) models⁴⁴.

A single system development methodology is not necessarily universally suitable for the development of all system types. Each SDLC process model has its weaknesses and strengths and is best suited for the development of specific kinds of systems. The selection of an appropriate SDLC model is dependent on several factors such as technical requirements, available resources, flexibility, and the goal of the system to be developed⁴⁵.

⁴³ GeeksforGeeks, 'System Development Life Cycle', 2024. <https://www.geeksforgeeks.org/system-development-life-cycle/> (accessed May 26, 2024).

⁴⁴ GeeksforGeeks, 'Software Development Models – SDLC Models', 2024. <https://www.geeksforgeeks.org/sdlc-models-types-phases-use/> (accessed May 26, 2024).

⁴⁵ CMS, 'SELECTING A DEVELOPMENT APPROACH', 2008. <https://www.cms.gov/files/document/selectingdevelopmentapproachpdf> (accessed May 26, 2024).

1.10.2 Waterfall SDLC

The waterfall methodology is an SDLC process model used to develop systems/solutions for a problem with a defined end goal. It is a widely used methodology with a stepwise approach where each stage of the model needs to be completed before the next stage is initiated [67], [68].

The methodology works well for the development of a solution where quality control is important in achieving the specified objectives [68]. As a result, it is frequently used in industries that require a high level of accuracy and reliability such as aerospace and defence⁴⁶. The use of the methodology was propelled by Dr. Winston Royce after publishing an article based on his experiences in developing systems for planning spacecraft missions, commanding, and post-flight analysis [69].

This methodology was considered due to its simplicity, ease of implementation, and proven track record in system/solution development [68]. The methodology is deemed applicable to this study since monitoring and reporting tools will need to be developed and implemented with a set goal of potentially improving PFM on deep-level mines.

Quality control is also important as the tools will need to be reliable and accurate in terms of the identification of poor PF performance to allow for proactive action to be taken. This is crucial as the tools can potentially have a direct impact on the electricity costs of various deep-level mine operations in terms of reactive energy charges and demand charges.

1.10.3 Breakdown of methodology

The use of SDLC models such as the waterfall methodology has been investigated by various researchers with multiple versions of the model having been proposed [68]. The high-level sequential stages of a typical SDLC model are presented in Figure 16.

⁴⁶ L. Hoory, C. Bottorff, and R. Watts, 'What is Waterfall Methodology?', 2022. <https://www.forbes.com/advisor/business/what-is-waterfall-methodology/> (accessed Nov. 05, 2022).

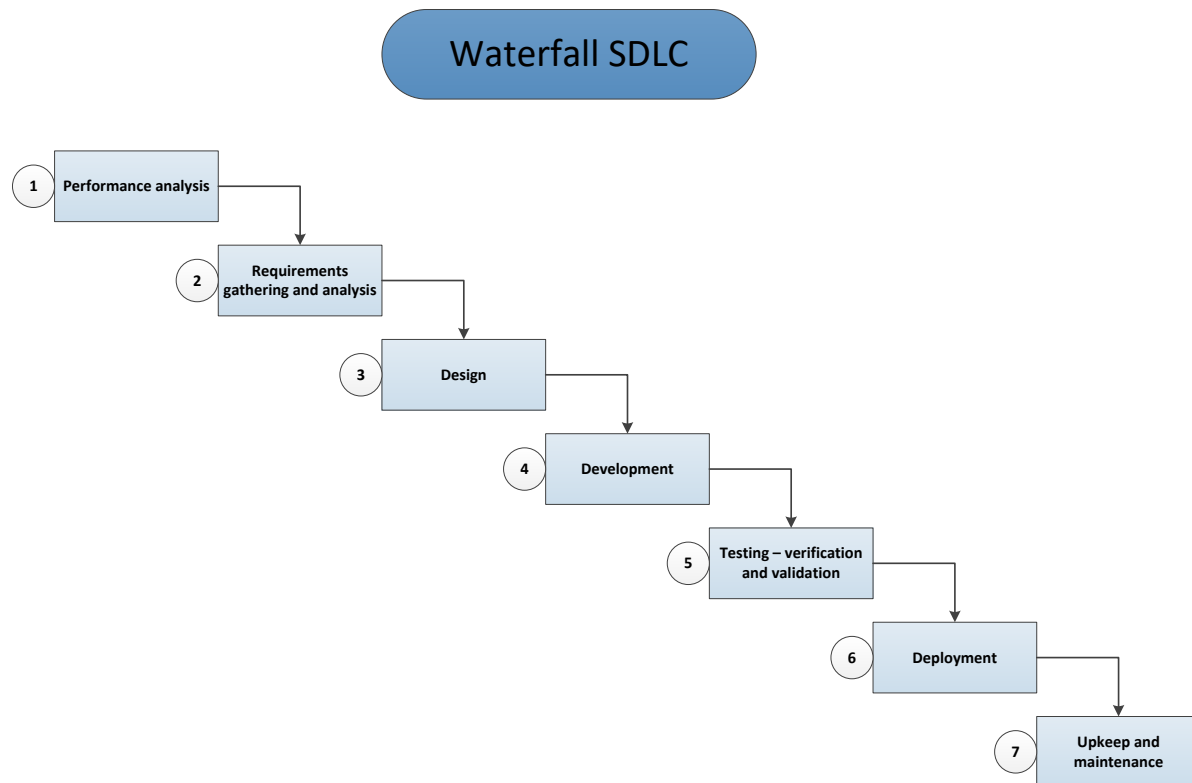


Figure 16: Waterfall SDLC model⁴⁷

Stage 1: The first stage of the SDLC model entails the analysis of available data to evaluate the current system's performance. Subsequently, inefficiencies and shortcomings in the current system are identified. Typical data sources used to extract system and energy data on deep-level mines include SCADAs and energy monitoring platforms such as iST ecWin. These data sources will be considered and discussed in greater detail in Chapter 2, Section 2.2.

Stage 2: During the second stage, the requirements for the new system are defined and analysed. The inefficiencies and shortcomings identified in stage 1 should be addressed with specific proposals for improvement. Furthermore, factors such as features, functions and capabilities are also outlined. This is an important stage in the SDLC, as this forms the basis from which the other stages are built.

The 5W1H method is a problem-solving approach that helps gather fundamental information about a given problem or situation to be analysed. It can therefore be used to structure the requirements of the power factor tools to be developed. Variants of the method include 5W2H, Five Ws, 6W1H and 6H⁴⁸. The application of the method will be discussed in greater detail in Chapter 2, Section 2.3.

⁴⁷ Adapted from: A. S. Gillis, 'What is Systems Development Life Cycle?', 2019. <https://www.techtarget.com/searchsoftwarequality/definition/systems-development-life-cycle> (accessed Nov. 05, 2022).

⁴⁸ CiToolkit, 'The 5W1H Approach: Asking Simple Questions For Great Results?', 2024. <https://citoolkit.com/articles/five-ws/> (accessed May 26, 2024).

Stage 3: The design stage establishes the approach that will be applied to provide a solution that will meet the requirements defined in stage 2. During this stage, the hardware, software, architecture, data sources, and services that will be employed are specified.

Pertaining to services/software products and software development tools. A software product is software that has been created to provide a service to users that satisfies their needs. Examples of software products can include products that facilitate online meetings and conferences such as Zoom or an image editing application such as Adobe Photoshop⁴⁹. Software development tools are computer programs that are utilised to create computer applications [70].

Business Intelligence (BI) software offers various analytical solutions in one software product. Companies use these solutions to gather, analyse, and transform data into user-friendly visualisations such as graphs, charts, and dashboards. These visualisations are used to interpret data and extract valuable insights. BI software typically comprises tools such as data warehouses, data visualisations, interactive dashboards, and reporting⁵⁰. This type of software may prove to be beneficial in improving decision-making and the management of systems.

The software products elected for the development and implementation of the PFM tools were:

- Microsoft Power BI
- Management Toolbox (MTB)
- Admin Toolbox (ATB)
- Reporting Toolbox (RTB)
- Process Toolbox (PTB)
- ASTIR

Microsoft Power BI is a freely available product. MTB, ATB, RTB, PTB, and ASTIR were chosen due to their availability on the case study deep-level mines. It should be noted that these software products have limited public accessibility. These software products will be discussed in greater detail in Chapter 2, Section 2.4, and Chapter 3, Section 3.2.4.

The architecture of a system refers to the structural design of the system and how the hardware and software components are organised. It provides a high-level overview of the interconnection between the various components by showcasing the relationship (data link)

⁴⁹ Wrike, 'What Is a Software Product?', wrike.com, 2021. <https://www.wrike.com/product-management-guide/software-product/#how-to-create-a-software-product-software-product-development-process> (accessed Jan. 11, 2023).

⁵⁰ A. Vaughan, 'Top Business Intelligence (BI) Software 2022', 2022. <https://technologyadvice.com/business-intelligence/> (accessed Jan. 21, 2023).

between them⁵¹. Additional background on system architecture and an overview on how the various software products are integrated into the development of the PFM tools will be discussed in greater detail in Chapter 2, Section 2.4, and Chapter 3, Section 3.2.4.

Stage 4: During the development stage the proposed product is developed according to the design specifications and the requirements outlined in stage 2.

Stage 5: During the testing stage the developed product is evaluated to determine whether it satisfies the requirements outlined in stage 2. Defects in the product are also identified and corrected during this stage. This will be achieved through the verification and validation of the PFM tools.

Verification will take place by means of results comparison with a reliable data source to ensure that the output of the tools is correct. The validation of the tools will be conducted through real-world implementation by means of a case study mine group across several PODs. Background on the verification and validation processes will be discussed in greater detail in Chapter 2, along with the approach used to verify and validate the tools in Sections 2.6.1 and 2.6.2, respectively.

Stage 6: After the product has passed the testing stage, it is ready to be deployed. During this stage, the product is made available to the end-user.

Stage 7: The final stage in the SDLC is the upkeep and maintenance stage. This involves updating and changing the product after it has been deployed based on end-user feedback or when faults are detected in the product^{52, 53}.

During the final stage of the SDLC, the tools are maintained, upgraded, or enhanced to ensure that it remains operational and performs as expected. This stage is crucial for ensuring the tools provide sustained opportunity for the users to maintain or further improve PFM on the deep-level mine operations. This stage typically lasts the longest and consumes a major portion of the SDLC financial resources; therefore, it should be an important project consideration as this stage continues until the product becomes obsolete [71]. The maintenance strategy to be implemented will be discussed in greater detail in Chapter 2, Section 2.8.

⁵¹ S. Jena, 'Difference between System Architecture and Software Architecture', 2020. <https://www.geeksforgeeks.org/difference-between-system-architecture-and-software-architecture/> (accessed Jan. 28, 2023).

⁵² A. Waseem, 'Waterfall Methodology – Ultimate Guide', 2022. <https://managementhelp.org/waterfall-methodology> (accessed Nov. 05, 2022).

⁵³ Adapted from: A. S. Gillis, 'What is Systems Development Life Cycle?', 2019. <https://www.techtarget.com/searchsoftwarequality/definition/systems-development-life-cycle> (accessed Nov. 05, 2022).

1.11 Document overview

This section provides an overview of the chapters within this document. The study consists of four chapters:

Chapter 1

This chapter provides background on the South African gold mining industry and electricity generation in South Africa. The challenges faced by deep-level gold mines and Eskom are highlighted, particularly the concerns regarding the escalating electricity prices and unreliable electricity supply given that gold mines are electricity-intensive operations. Background on PFM is provided and its influence on Eskom and gold mines is revised along with PFM tactics.

A literature review is presented which explored the current industry approach towards PFM and the latest technologies utilised with the aim of developing various tools to improve the PFM on deep-level gold mines. The literature review and relevant background were used to formulate the problem statement from which the study objectives were developed and stated. Background information on SDLC methodologies is presented, including a breakdown of the Waterfall SDLC methodology, which will be implemented in the development of the PFM tools.

Chapter 2

This chapter describes each stage of the waterfall SDLC methodology that was applied to develop the various tools to improve PFM on deep-level gold mines. The waterfall SDLC process model was selected to guide the development of the tools. The background and literature studies revised in Chapter 1 were consulted to assist in establishing the approach to each stage in the methodology.

Chapter 3

The methodology formulated in Chapter 2 is applied in this chapter to develop the various PFM tools. The tools are implemented on a case study gold mine group to establish its impact on PFM across various deep-level gold mines. The proposed solution will be verified and validated to ensure the objectives stated in Chapter 1 are achieved. Furthermore, the results will also be interpreted and presented within this chapter.

Chapter 4

This chapter concludes the study and provides an executive summary of the efficacy of implementing the proposed PFM tools on deep-level gold mines. Lastly, recommendations for future work concerning the topic are provided.

CHAPTER 2

2 DEVELOPMENT OF POWER FACTOR MONITORING AND REPORTING TOOLS

2.1 Introduction

The main objective of the study is to develop monitoring and reporting tools that have the potential to improve the PFM on deep-level mines. Section 1.7 investigated PFM to establish the current industry approach and tools utilised and developed to improve and manage power factors.

From the literature review in Section 1.7, it is evident that the use of monitoring tools forms the basis of most PFM approaches, whilst other tools such as reporting, notifications, and ranking and prioritisation are neglected. The use of web-based tools also shows promise considering its advantages in remote monitoring capabilities and ease of access but was only incorporated in a few studies.

Moreover, research on PFM within the mining industry was limited. This further reinforced the need to explore the development and use of tools such as monitoring and reporting to aid in improving the management of power factors on deep-level gold mines.

Background on system development methodologies were presented in Section 1.10 from which the waterfall SDLC process model was selected to develop the tools to improve PFM on deep-level gold mines. This methodology, which consists of seven stages as illustrated in Figure 16, was chosen for its simplicity and proven effectiveness in system/solution development. This chapter examines the implementation of the methodology.

2.2 Stage 1: Performance analysis

During the first stage of the waterfall SDLC, the PF performance of various deep-level mine operation PODs are established and ranked based on their PF performance relating to energy charges. This allows for the identification of PODs with poor performance that need to be prioritised for improved PFM and further investigation into the current PFC. Study Objectives I and II are addressed in this stage. The performance analysis process is conducted by means of a five-step approach as showcased in Figure 17.

Step 1: The first step of the performance analysis process involves establishing the purpose of the analysis and the relevant metrics that will be used to measure performance⁵⁴.

The purpose of the analysis can be derived from the objectives outlined in Section 1.9. This analysis intends to establish the current PF performance of various deep-level mine operations (Objective I) as well as rank these operations based on their performance to enable prioritisation of operations for improvement (Objective II). The insights gathered from carrying out the performance analysis process will also assist in developing the PFM tools to be implemented in fulfilment of Objectives III and IV.

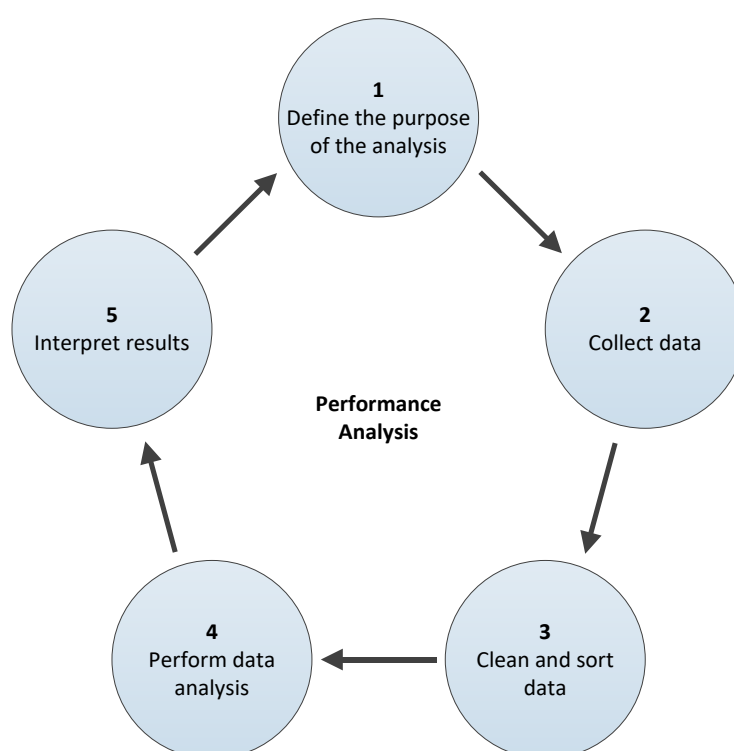


Figure 17: Performance analysis process flow diagram⁵⁵

As specified from the background in Section 1.3.3, facilities pay penalties during the winter months on their excess reactive energy usage in the case of inadequate PF performance; therefore, the analysis is focused on examining the chosen performance metrics specifically during the winter months. The following metrics have been selected to evaluate the PF performance at the POD of various deep-level mine operations:

The PF of the operation. The average PF for an operation needs to be considered, as the penalties on the excess reactive energy usage are based on a facility PF below 0.96.

⁵⁴ D. Pickell, 'What Is the Data Analysis Process? 5 Key Steps to Follow', 2021. <https://www.g2.com/articles/data-analysis-process> (accessed Dec. 11, 2022).

⁵⁵ Adapted from: D. Pickell, 'What Is the Data Analysis Process? 5 Key Steps to Follow', 2021. <https://www.g2.com/articles/data-analysis-process> (accessed Dec. 11, 2022).

The PF of a POD can be determined by using Equation 1:

$$\text{Power Factor (PF)} = \frac{\text{Active Power (P)}}{\text{Apparent Power (S)}}$$

Excess reactive energy consumption. This is only applicable during the Eskom standard and peak-time energy usage periods and is used to determine the penalties on the Eskom electricity bill during the winter months. As discussed in Section 1.3.3, excess reactive energy is only recorded at power factors below 0.96 or reactive energy in excess of 30% of the recorded active energy measured during peak and standard electricity usage periods. The first step is to formulate the non-excess reactive energy by manipulating Equation 1 and Equation 3 where P denotes the active energy, S the apparent energy, and Q the reactive energy.

$$\text{Power Factor (PF)} = \frac{P}{S}$$

Set the PF equal to 0.96:

$$0.96 = \frac{P}{S}$$

$$P = 0.96S$$

Refine Equation 3 to define S in terms of P and Q and substitute into the expression $P = 0.96S$:

$$P = 0.96\sqrt{P^2 + Q^2}$$

Thereafter, the expression can be simplified:

$$P^2 = \left(0.96\sqrt{P^2 + Q^2}\right)^2$$

$$P^2 = 0.9216P^2 + 0.9216Q^2$$

$$0.0784P^2 = 0.9216Q^2$$

$$\sqrt{0.0784P^2} = \sqrt{0.9216Q^2}$$

$$0.28P = 0.96Q$$

$$Q = \frac{0.28}{0.96}P$$

Once simplified, the non-excess reactive energy can be expressed as:

Equation 15: Non-excess reactive energy

$$Q_{Non-excess} = 0.2916666667P_{Total} \approx 0.3P_{Total}$$

The excess reactive energy may then be expressed as:

Equation 16: Excess reactive energy

$$Q_{Excess} = Q_{Total} - Q_{Non-excess}$$

$$Q_{Excess} = Q_{Total} - 0.3P_{Total}$$

Where the PF is equal to or below 0.96.

The penalties paid by the operation. The penalties are determined based on the excess reactive energy which is billed against a fixed Eskom tariff as outlined in Table 1 and Appendix C. This alongside the excess reactive energy will assist in ranking the operations that need to be prioritised for improved PFM or upgrades in PFC equipment.

The reactive energy charge (penalty) applied during the high-demand season can be calculated as follows:

Equation 17: Reactive energy charge

$$\text{Reactive Energy Charge (Penalty)} = Q_{Excess} * \text{Eskom Tariff}_{Excess \text{ reactive energy}}$$

Maximum apparent power consumption. The increase in reactive power due to a poor PF leads to an increase in the apparent power consumption as outlined in Section 1.3.3 and Appendix C. This could potentially lead to an operation exceeding their agreed NMD which, in turn, will lead to penalties that are charged at much higher rates than allocated to excess reactive energy. The maximum demand can be determined by calculating the apparent power and taking the maximum value recorded over the monthly Eskom bill period. This can be formulated by adjusting Equation 3 to calculate the apparent power:

$$\text{Apparent power } (S)^2 = \text{Active power } (P)^2 + \text{Reactive power } (Q)^2$$

$$\sqrt{(S)^2} = \sqrt{(P)^2 + (Q)^2}$$

$$S = \sqrt{(P)^2 + (Q)^2}$$

The maximum demand is equal to the maximum resulting value of $\sqrt{(P)^2 + (Q)^2}$ over the selected period. Thus, the maximum demand can be described as:

Equation 18: Maximum demand

$$S_{Max} = \text{MAX} \left(\sqrt{(P)^2 + (Q)^2} \right)$$

Network demand charge. The network demand charge is based on the maximum apparent power consumption during off-peak, standard, and peak-time energy usage periods and is billed monthly. This will indicate the financial impact of the poor PF on the monthly demand charge due to an increase in maximum apparent power consumption when comparing year-on-year performance.

$$\text{Network Demand Charge} = S_{Max} * \text{Eskom tariff}_{\text{Network demand}}$$

Excess apparent power consumption. This provides an indication of the additional consumption in apparent power due the POD PF performance. Excess apparent power exists when the PF is below 1 (not unity). Thus, if there is reactive power in the system, there is also a resulting excess apparent power present.

Therefore, by eliminating the excess apparent power from the system, the PF will return to unity. This can be formulated into an equation by adjusting Equation 1 and setting the PF equal to 1 as follows:

Equation 19: Power factor expression at unity with excess apparent power considered

$$\text{Power Factor (PF)} = \frac{P_{At \max S}}{S_{Max} - S_{Excess}} = 1$$

From Equation 18 the excess apparent power can be expressed as:

Equation 20: Excess apparent power

$$S_{Excess} = S_{Max} - P_{At \max S}$$

Excess network demand charge. This provides an indication of the additional costs accrued on the network demand charge due to the presence of reactive power in the system. The excess network demand charge can be calculated as follows:

Equation 21: Excess network demand charge

$$\text{Excess Network Demand Charge} = S_{Excess} * \text{Eskom tariff}_{\text{Network demand}}$$

Capacitor bank downtime. This metric is linked to the reactive energy consumption and PF performance. When the capacitor banks have stopped or failed it will lead to a reduction in POD PF (most likely below 0.96), leading to excess reactive energy usage which will be penalised on the Eskom bill during the winter months. A strong correlation is expected between the capacitor bank downtime and the reactive energy penalties accrued on the Eskom electricity bill.

The capacitor bank downtime will be estimated based on the PF data of the POD and incomers as well as confirmation from site personnel regarding capacitor bank stoppage or fault. This is due to the absence of power consumption data for the capacitor banks to verify remotely of a stoppage.

Table 3 provides an overview of the aforementioned metrics and their units of measure. These performance metrics will form the foundation of the performance analysis and enable the gathering of valuable insights once the results have been interpreted.

Table 3: Performance metrics for power factor analysis

Performance Metrics	
Metric	Unit of Measure
Power factor	Ratio
Excess reactive energy consumption	reactive kilovolt-ampere-hour [kVAh]
Reactive energy charges	Rand [R]
Maximum apparent power consumption	kilovolt-ampere [kVA]
Network demand charge	Rand [R]
Excess apparent power consumption	kilovolt-ampere [kVA]
Excess network demand charge	Rand [R]
Capacitor bank downtime	Hours [h]

Step 2: After the purpose and the performance metrics have been defined, the data collection process can commence⁵⁶. Data collection is the process of gathering data based on the specified performance metrics outlined in step 1. It is crucial to ensure the acquisition of accurate and trustworthy data by using reliable sources, as this assures the validity of the results and decisions made based on the analysis of the extracted data⁵⁷.

The performance data is collected from internal and external sources. The internal sources are SCADAs and the iST ecWin services utilised by the mines, while the external data source

⁵⁶ D. Pickell, 'What Is the Data Analysis Process? 5 Key Steps to Follow', 2021. <https://www.g2.com/articles/data-analysis-process> (accessed Dec. 11, 2022).

⁵⁷ Tutorialspoint, 'Data Analysis - Process', 2022. https://www.tutorialspoint.com/excel_data_analysis/data_analysis_process.htm (accessed Dec. 13, 2022).

is the Eskom electricity bills of the operation's PODs. The PODs of each operation will be used to establish the PF performance.

A SCADA is a system of hardware and software components that enable industrial firms to control their processes locally or remotely and directly communicate with devices such as valves, sensors, motors, and more. Furthermore, it allows for real-time data monitoring, collection and processing⁵⁸. The use and benefits of SCADA in industrial environments have been well documented [72], [73].

The majority of the mines utilise a SCADA system to store digital data of various systems [74]. Each system component has a specified address stored on a PLC by which it can be identified by on the SCADA. This address is referred to as a tag name [75]. The SCADA continuously communicates with the PLCs to extract the data and stores it in a log file. An outline of a basic SCADA system is presented in Appendix E.

iST ecWin is an additional platform utilised by South African mines to monitor and display energy resource information online⁵⁹. It allows users to view energy usage profiles of various systems, statistics, and permits data extraction. The Eskom electricity bill, as discussed in Section 1.3.3, provides a breakdown of the energy-related costs billed against the operation's POD. An example of an Eskom electricity bill is available in Appendix C, Figure 83.

Therefore, it is important to gain access to these internal and external sources, as their data will form the foundation of the performance analysis. Table 4 provides an overview of the data sources for the various performance metrics.

Table 4: Performance analysis data sources

Data Sources	
Performance Metric	Source
Power factor [Ratio]	SCADA & iST ecWin
Excess reactive energy consumption [kVArh]	SCADA & iST ecWin & Eskom bills
Reactive energy charges [R]	Eskom bills
Maximum apparent power consumption [kVA]	SCADA & iST ecWin & Eskom bills
Network demand charge [R]	Eskom bills
Excess apparent power consumption [kVA]	Eskom bills
Excess network demand charge [R]	SCADA & iST ecWin & Eskom bills
Capacitor bank downtime [h]	SCADA & iST ecWin

⁵⁸ Inductive Automation, 'What is SCADA? Supervisory Control and Data Acquisition', 2018. <https://inductiveautomation.com/resources/article/what-is-scada> (accessed Dec. 13, 2022).

⁵⁹ iST, 'ecWIN | Integrate Solve Together', 2022. <https://ist.co.za/product/ecwin> (accessed Dec. 13, 2022).

Step 3: Once the relevant performance data has been extracted, the data must first be cleaned and sorted. Considering that the data is gathered from various sources, it needs to be restructured and reviewed to identify errors or irrelevant/redundant information that should be excluded. During this step, the data is sorted based on the performance metrics to enable data analysis to take place. This is done by structuring the data into rows and columns on a spreadsheet⁶⁰.

Before the data analysis can commence, the data must first be cleaned by removing duplicate data points and anomalous or erroneous data that could skew the analysis; thus, this process is imperative to ensure the data analysis results provide logical outputs.

Step 4: During this step, the restructured and cleaned data is analysed to determine the performance metrics of the various deep-level mine operations' PODs as outlined in Table 3. Additionally, the operations are to be ranked based on PF performance and reactive energy charges to allow the identification of poor-performing operations.

Step 5: The final step of the performance analysis process is to interpret the performance metric results. This allows valuable insight to be extracted from the first four steps⁶¹. The expected insights to be gathered are:

- Which operations are critical performers and need to be prioritised for improvement?
- What are the total reactive energy penalties due to poor PF performance?
- What is the impact on the apparent power consumption and demand charges?

These insights will assist with the requirements gathering and analysis stage of the SDLC for the development of the PFM tools.

⁶⁰ Tutorials Point, 'Data Analysis - Process', 2022. https://www.tutorialspoint.com/excel_data_analysis/data_analysis_process.htm (accessed Dec. 13, 2022).

⁶¹ D. Pickell, 'What Is the Data Analysis Process? 5 Key Steps to Follow', 2021. <https://www.g2.com/articles/data-analysis-process> (accessed Dec. 11, 2022).

2.3 Stage 2: Requirements gathering and analysis

The requirements gathering and analysis stage can now commence with the current PF performance of the various mine operations established. The inefficiencies or shortcomings identified during the initial stage are to be addressed with proposals for improvement.

2.3.1 Requirements gathering

In order to analyse the context of the PF situation outlined by the performance analysis, the *5WH* framework is employed. This framework is a simple and effective method that can be utilised in project management to ask applicable questions to better understand a problem and develop a suitable solution [76], [77].

The *5WH* approach to gathering information or solving a problem originated as a method to assist journalists in formulating their stories. This method is similar to the methodical fact-finding approach used in law enforcement and by the police to solve crimes [78]. The six questions utilised to gain clarity are presented in Figure 18.

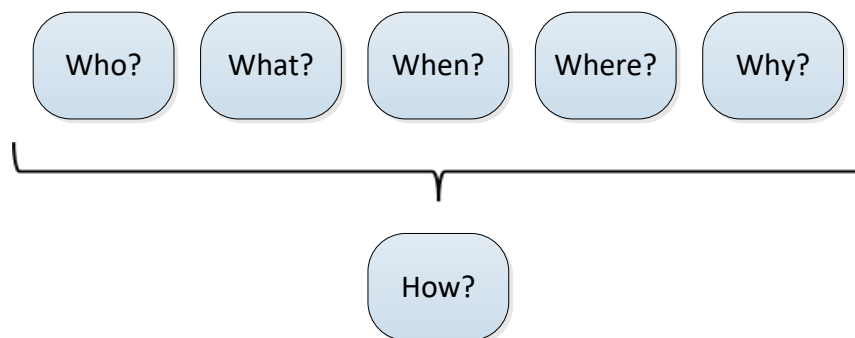


Figure 18: 5WH framework

Product managers utilise this technique during product development to organise their thoughts and planning in a systematic way to address the fundamental questions of a complex problem^{62, 63}. It is also employed by systems engineers to compile a set of high-level requirements based on the needs, wants, and expectations of various stakeholders [76].

During the requirements gathering section, the *5W* questions are addressed while the *H*, “How?”, question is addressed during the analysis section. Table 5 provides an example of the *5W* questions and their answers.

⁶² R. Singh, ‘The 5 W’s in business: Definition, practices and benefits’, 2020. <https://www.appvizier.com/magazine/operations/project-management/the-5-ws-in-business> (accessed Dec. 29, 2022).

⁶³ ProductPlan, ‘5 Ws and H’, 2022. <https://www.productplan.com/glossary/5-ws-and-h/> (accessed Dec. 29, 2022).

Table 5: Requirements gathering through 5W questions example

5W Questions and Answers	
Who?	
Question(s)	Who will be using the PF tools?
Answer(s)	Relevant site personnel.
What?	
Question(s)	What type of tools are required?
Answer(s)	PF monitoring, reporting, and notification tools.
When?	
Question(s)	When will the tools be used?
Answer(s)	The tools will be used daily.
Where?	
Question(s)	Where will the tools be accessed?
Answer(s)	The tools will be accessed remotely.
Why?	
Question(s)	Why is it required to develop these tools?
Answer(s)	There is scope to reduce PF penalties on the Eskom electricity bill.

Table 6 provides an example summary of the resulting requirements list to be analysed.

Table 6: List of requirements example

List of Requirements	
5W	Requirements
Who	Relevant site personnel must have access to the tools.
What	- PF monitoring. - PF reporting. - PF notification.
When	Users must have daily access to the tool.
Where	Users must be able to access the tools remotely.
Why	Reduce PF penalties on the Eskom electricity bill.

The templates of Table 5 and Table 6 are available in Appendix F. Once the final list of requirements is established, the analysis of the requirements can proceed.

2.3.2 Requirements analysis

Once the requirements are established from answering the 5W questions, they are analysed to establish the tools and features that will be required to address the identified problems. This section is encapsulated by the “How?” question which represents the *H* in the 5WH framework. Table 7 provides an example of the requirements analysis which is used to develop the tools and features for this study.

Table 7: Requirements analysis example

Requirements Analysis	
Requirements	Analysis (<i>H – How?</i>)
Relevant site personnel must have access to the tools.	Relevant personnel such as management and the shaft engineer will be given access to the tools.
PF monitoring.	Users will be able to monitor the latest PF data of an operation as well as the historic data available via a monitoring platform.
PF reporting.	Users will have access to a daily report via email that provides an overview of the historic PF performance.
PF notifications.	Users will be notified of sudden deviations in PF performance via a mobile application notification.
Users must have daily access to the tools.	The tools and services will be continuously accessible online by means of an internet browser.
Users must be able to access the tools remotely.	Users will be able to access the tools remotely via a web browser (internet access is required).
Reduce PF penalties on the Eskom electricity bill.	The monitoring, reporting, and notification tools will assist users to improve the management of their power factors by keeping them informed and enabling pro-active measures to be taken when issues arise.

The resulting list of tools and features are derived from the requirements analysis. Table 8 provides an example of the list of tools and features formulated from Table 7. The templates of Table 7 and Table 8 are available in Appendix F.

Table 8: List of tools and features example

List of Tools and Features	
Tools	Features
Monitoring	• Latest daily PF profile (updated every hour). • Historic PF profiles (period selection).
Reporting	• Historic PF performance. • Site ranking based on PF performance.
Notification	• Variable alarm trigger (can adjust limits used to activate alarm and alarm trigger frequency). • Smartphone notification.

2.4 Stage 3: Design

During the design stage, the approach used to develop the PFM tools and features is defined to ensure that the requirements set out in stage 2 are met. This entails providing details regarding user system requirements, data sources, system architecture, services/software products utilised, or the software development tools employed to develop the designated tools.

Table 9 provides an example summary of the design specifications that will be determined for each tool before proceeding with the development phase:

1. Web-based monitoring.
2. Daily performance report.
3. Notification system.

Table 9: Tool design specifications example

Design Specifications		
Category	Specifications	
User system requirement	Hardware	Any device that has internet connectivity and can run a web-browser.
	Software	Operating system such as Microsoft Windows and browser software such as Google Chrome.
Data source(s)	SCADA	
Software product(s) and development tool(s)	Microsoft Power BI	
System architecture	Diagram illustrating the connection between the various components of the tool.	

User system requirements: System requirements denote the hardware and software configuration a system must have for a software application to run smoothly on the installed device⁶⁴. Therefore, it is important to take this into account when developing software tools to ensure compatibility with most devices in use today. A high-level overview of the system requirements will be provided for each PF tool being developed.

Data sources: The use of data is integral to the functionality of the PF tools to be developed. Therefore, it is important to acquire data from trusted sources. Referring back to stage 1 of the SDLC, three main potential data sources were identified to conduct the performance analysis: the SCADA of each mine operation, iST ecWin, and Eskom electricity bills.

Services/software products utilised and software development tools: The requirements and features from stage 2 for each tool is taken into account when selecting an appropriate service/software product for development. Table 10 provides an overview of the typical features expected from monitoring, reporting, and notification tools. BI software options are also presented alongside dedicated software products that could be employed to create the designated PF tools.

It should be noted that most of the BI software listed under monitoring also have reporting and notification capabilities built in. A list of free BI software is provided in Appendix G.

⁶⁴ Technopedia, 'What are System Requirements? - Definition from Techopedia', 2015. <https://www.techopedia.com/definition/4371/system-requirements> (accessed Jan. 10, 2023).

Table 10: Data tool features and software products options⁶⁵

Features and Software Product Options		
Data tool	Typical Features	Software Product Options
Monitoring	• Web-based to allow for remote access online • User-friendly dashboard/interface. • Ability to import and export data from multiple sources • Data visualisation and dataset viewing customisation (period viewing selection) • Real-time data access or system-appropriate data interval access. • Data loss indication	• Tableau • Power BI • Looker • Sisense • Domo • Process Toolbox (PTB) • Qlik Sense • Posit • MicroStrategy • Wattics • Enerit • Quentic
Reporting	• Web-based to allow for remote access online • User-friendly dashboard/interface • Data visualisation options and customisation • Report scheduling (automatic report generation and distribution) • Pre-built templates • Data integration	• Whatagraph • Zoho Analytics • Wrike • DashThis • MesiterTask • Datapine • Reporting Toolbox (RTB) • Excel • Octoboard • Wattics • Enerit • Quentic
Notifications	• Event triggered • User-friendly interface • Add, edit, and manage notifications • Audience segmentation (select relevant personnel to receive notification) • Integration with existing systems • Multimodal notifications (different communication channels)	• Process Toolbox (PTB) • Power BI • Wattics • Tableau • Looker • Sisense • DOMO • MicroStrategy • Quentic • Qlik Sense

⁶⁵ Adapted from: (1) A. Vaughan, 'Top Business Intelligence (BI) Software 2022, 2022. <https://technologyadvice.com/business-intelligence/> (accessed Jan. 21, 2023).

(2) Microsoft, 'Power BI Desktop-Interactive Reports', 2019. <https://powerbi.microsoft.com/en-us/desktop/> (accessed Jan. 12, 2023).

(3) J. Stangarone, '6 essential elements of modern enterprise reporting software', 2019. <https://www.mrc-productivity.com/blog/2019/08/6-essential-elements-of-great-enterprise-reporting-software/> (accessed Jan. 18, 2023).

(4) T. Das, 'How to Choose an Ideal Reporting Tool: 8 Features to Look For', 2021. <https://www.makeuseof.com/how-to-choose-reporting-tool/> (accessed Jan. 18, 2023).

(5) B. Aston, '10 Best Reporting Tools & Software Of 2023', 2022. <https://thedigitalprojectmanager.com/tools/best-reporting-tools/> (accessed Jan. 18, 2023).

(6) Antonio, 'ISO 50001 Energy Management Software Standard - Certification, Requirements', 2016. <https://www.wattics.com/iso-50001-energy-management/> (accessed Jan. 18, 2023).

(7) Enerit, 'Systematic Energy Management Software | ISO 50001 Software', 2013. <https://enerit.com/> (accessed Jan. 18, 2023).

(8) Quentic, 'ISO 50001 software', 2021. <https://www.quentic.com/iso-50001-software/> (accessed Jan. 18, 2023).

(9) G2, 'Top 10 Microsoft Power BI Desktop Alternatives 2023', 2023. <https://www.g2.com/products/microsoft-microsoft-power-bi-desktop/competitors/alternatives> (accessed Jan. 18, 2023).

System architecture: The system architecture is used to guide the development and implementation of the system. It is, therefore, instrumental in determining the performance, scalability, and maintainability of the system⁶⁶. This ensures that the requirements and intended purpose of the future product are met as outlined during the requirements gathering stage.

Maheepala *et al.* presents a high-level architecture of a proposed system with the purpose of fulfilling energy monitoring, analysis, reporting, and warning notifications for energy auditing [56]. The components of the proposed system are similar to the set of tools to be developed for this study and will, therefore, be consulted to construct system architectures during the design stage. The proposed system architecture of [56] is presented in Figure 15.

A high-level system architecture for each PF tool will be developed. A collective system architecture will be provided that condenses the tools by integrating the various architectures into one system architecture.

Once the design stage is complete, the development stage can commence based on the information compiled from stages 1 to 3.

2.5 Stage 4: Development

During the development stage the monitoring, reporting, and notification tools are developed based on the designated features and design specifications, as outlined in stages 2 and 3, in partial fulfilment of Objectives III and IV. The primary goal of this stage is to convert the product design concept into a working system that addresses the documented requirements⁶⁷. An overview will be provided in terms of the various PF tools developed along with their respective features.

2.6 Stage 5: Testing

The testing stage is initiated once the PFM tools, along with all their features, are developed. During this stage, the monitoring, reporting, and notification tools are subject to verification and validation to ensure the requirements outlined in stage 2 are satisfied. The key objectives in verification and validation are to identify and resolve system errors before the product is deployed [79].

⁶⁶ InterviewBit, 'System Architecture - Detailed Explanation', 2022. <https://www.interviewbit.com/blog/system-architecture/> (accessed Jan. 28, 2023).

⁶⁷ S. Halwai, 'SDLC Development Phase – A Detailed Overview', 2021. <https://www.openxcell.com/blog/development-phase-in-sdlc/> (accessed Jan. 29, 2023).

The latest international standard vocabulary for systems and software engineering, from ISO/IEC/IEEE, defines verification and validation (V&V) as follows: “The process of determining whether the requirements for a system or component are complete and correct, the products of each development phase fulfil the requirements or conditions imposed by the previous phase, and the final system or component complies with specified requirements” [80].

The verification and validation process of the tools are split into two separate sections. The testing process is initiated with the verification of the tools and precedes the validation of the tools. Verification by itself can be described as the process of establishing whether the product is correct and truthful with regards to its specifications and output [79], [80], [81].

Validation can be described as the process of establishing the fitness of a product for its intended use [79], [80], [81].

The verification and validation of the tools are discussed in Sections 2.6.1 and 2.6.2 respectively.

2.6.1 Verification of power factor management tools

Verification will take place by means of results comparison with a reliable data source to ensure that the output of the tools is correct. The expected tool output will be calculated in Excel and compared to the actual output of the tool.

The error percentage will be determined by establishing the difference between the expected output and the actual output divided by the expected output multiplied by a hundred percent as shown in Equation 22 [82].

Equation 22: Error percentage

$$\text{Percentage Error} = \frac{\text{Actual Output}}{\text{Expected Output}} \times 100\%$$

This equation will be used for singular outputs; for example, when calculating the total excess reactive energy usage over 31 days. The theoretical expected percentage error of the tools is zero, as the tools will be replicating the calculations done in Excel by using the same data source.

The mean absolute percentage error (MAPE) will be used to determine the accuracy of large outputs such as the datasets used by the tool to create and display graphs. The MAPE is one of the most widely used statistical methods for determining accuracy, especially with prediction models [83] [84], and is easy to interpret and explain to stakeholders.

The MAPE is calculated by taking the absolute error (absolute difference between the actual and expected output) and dividing it by the observed value (expected output) for each period. The resulting percentages are then averaged. A resulting MAPE value of below 10% is deemed to be highly accurate for industrial and business data [84]. The value of MAPE is expressed by Equation 23.

Equation 23: Mean absolute percentage error (MAPE)

$$MAPE = \frac{1}{n} \sum_{t=1}^n \frac{|\hat{y}_t - y_t|}{y_t} \times 100\%$$

where n denotes the sample size, $\hat{y}_t$ the actual output of the tool for time point t , and y_t the expected output. It should be noted that the MAPE can be influenced by values of a low range, which could result in high MAPE values or even undefined when the actual output, $\hat{y}_t$, is equal to zero.

Visual illustrations of how the expected output and the actual tool output compare will also be utilised alongside the MAPE. This will not be used to analyse and interpret the output data of the tool but rather provides a visual comparison between the expected and actual tool output.

The relevant equations used to verify the tools will be outlined during the verification in Section 3.2.6 after the tools are designed and developed.

2.6.2 Validation of power factor management tools

The validation of the tools will be conducted through real-world implementation by means of a case study mine group across several PODs, in fulfilment of Objectives III and IV. This will determine whether the tools satisfy the intended use of improving the PFM on deep-level mines in fulfilment of Objectives V and VI. For example, if capacitor bank downtime is reduced, it may assist in improving the PFC performance of a mine's operations. Thus, achieving the goal of improving PFM.

The performance metrics outlined in Section 2.2 will be used to measure the impact of the PFM tools before and after implementation. The tools will be validated based on these results.

2.6.3 Data verification and validation

Referring to Sections 2.2 and 2.4, the data sources used by the tools are iST ecWin and the mine operation SCADA. These data sources are deemed verified and credible, as they are currently being used for daily energy management decision-making and performance monitoring.

The accuracy of the data will be determined by calculating the following performance metrics:

- Total active energy consumption [kWh]
- Maximum demand [kVA]
- Total excess reactive energy consumption [kVArh]

As discussed in Section 1.3.3, the total active energy consumption is measured throughout the day, whilst the maximum demand and the total excess reactive energy is only measured during standard and peak TOU periods. This will be considered when calculating the performance metrics. Figure 7 provides an overview of the TOU periods.

The results will subsequently be compared to the figures presented in the monthly Eskom electricity bill and validated based on the MAPE value.

2.7 Stage 6: Deployment

Once the testing stage has concluded, the tools are ready to be deployed. During this stage, the tools are made available to the end-users. Relevant deep-level mine operation personnel will be given access to the monitoring, reporting, and notification tools for daily use with the aim of improving the PFM of the operation.

The relevant personnel includes onsite personnel from the engineering department such as the shaft engineer, foremen, and electricians responsible for maintaining the PF equipment. Offsite personnel such as the energy management department and energy management contractors will also have access to these tools to allow for intradepartmental and contractor-client awareness and communication to proactively attend to PF issues.

The details of the personnel who will gain access will be handled by means of an operation-by-operation case. The official lines of communication will be adopted based on the operation's communication structures to simplify integration.

2.8 Stage 7: Upkeep and maintenance

The upkeep and maintenance stage of the SDLC commences once the tools are officially deployed and in use.

The type of maintenance required may vary over the lifespan of a system/solution. It can range from a routine maintenance task such as rectifying a small software error to a large maintenance event such as migrating the source code to a new program language to enhance reliability and maintainability.

The main types of maintenance as indicated by the International Standards of ISO/IEC/IEEE are as follows:

Adaptive maintenance: “modification of a software product, performed after delivery, to keep a software product usable in a changed or changing environment” [71].

Additive maintenance: “modification of a software product performed after delivery to add functionality or features to enhance the usage of the product” [71].

Emergency maintenance: “unscheduled modification performed to temporarily keep a system operational, pending corrective maintenance” [71].

Perfective maintenance: “modification of a software product to provide enhancements for users, improvements of information for users, and recording to improve software performance, maintainability or other software attributes” [71].

Preventative maintenance: “modification of a software product after delivery to correct latent faults in the software product before they occur in the live system” [71].

These types of maintenance can be further classified into corrections and enhancements. Corrections refer to “software change that addresses and implements problem resolutions to recover gaps and to make software operational enough to meet defined operational requirements” [71]. Enhancements represent “software change that addresses and implements a new requirement” [71]. Figure 19 illustrates the relationship between the maintenance classifications and types of maintenance.

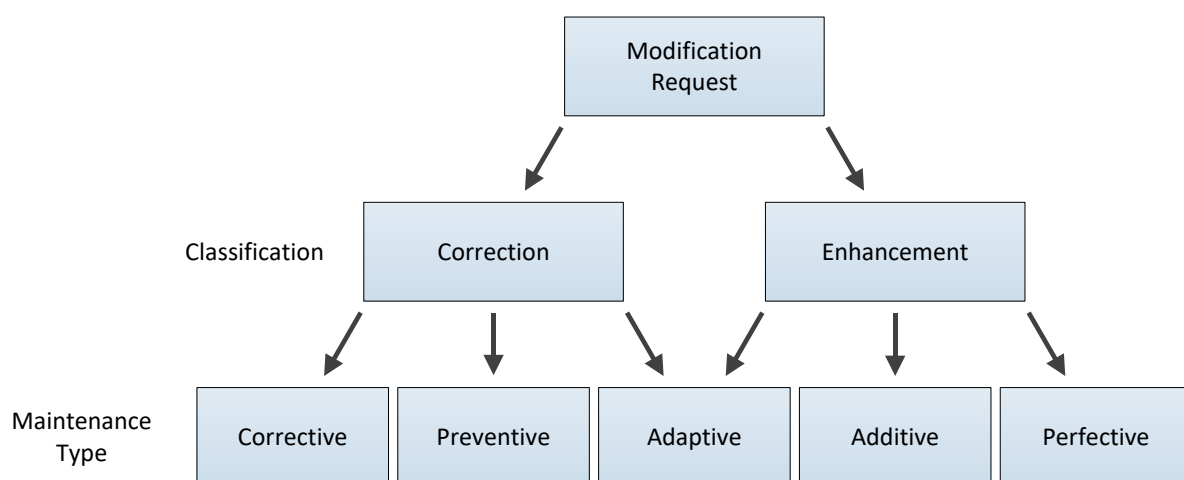


Figure 19: Modification request structure [71]

A modification request or a change request is typically represented by an information piece that identifies and describes proposed changes to a product or service [71]. Once it has been put forth, the request is classified, and the type of maintenance is established. The maintenance type can also be sub-divided into “scheduled”, “unscheduled”, and “emergency” categories, which assists in prioritising the modification requests to ensure the most urgent maintenance tasks take precedence [71], [86].

The modification request initiates the maintenance process [86], [87]. The IEEE standard for system maintenance outlines and arranges the key activities that need to take place during the maintenance process as depicted in Figure 20.

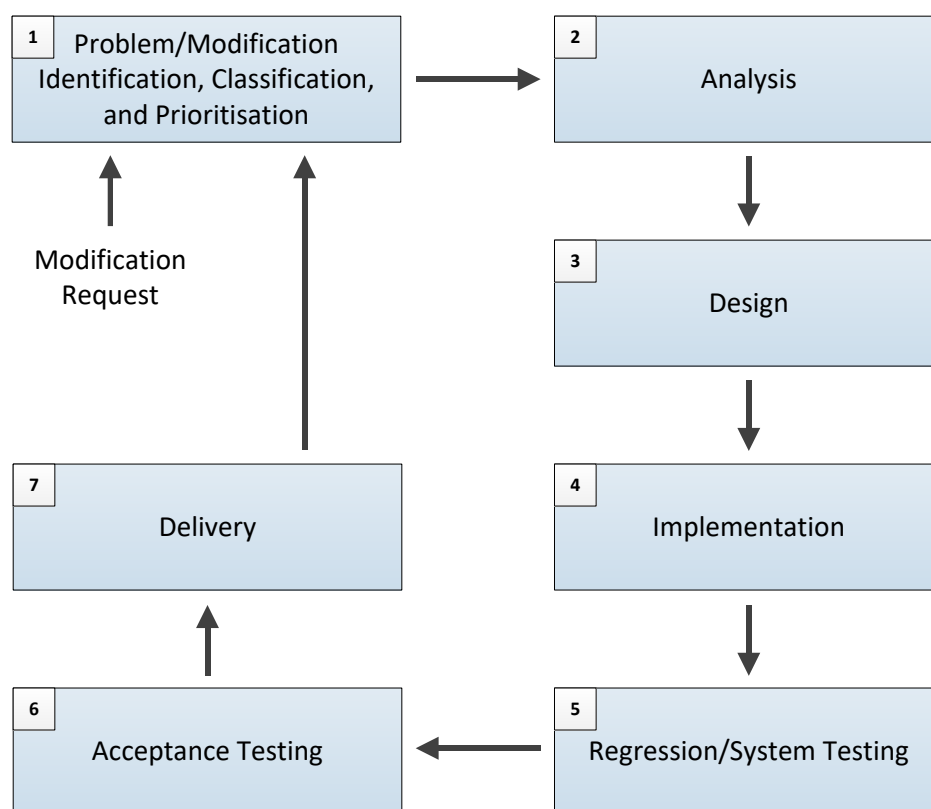


Figure 20: IEEE Maintenance process [86], [87]

Phase 1: System modifications are identified and classified based on the various maintenance types as displayed in Figure 19. Additionally, an initial priority ranking is assigned to each modification request [86].

Phase 2: During the analysis phase, the feasibility and scope of the modification request is established. A preliminary plan is developed for the subsequent phases [86].

Phase 3: All existing system documentation and the output of the analysis stage (requirements, affected elements, test strategy, and implementation plan) are used to design the requested system modification [86].

Phase 4: The results of the design phase along with the system documentation are used to guide the implementation of the requested system modification [86].

Phase 5: During this phase the system undergoes regression testing to validate the implemented modification request to ensure that the system changes did not introduce faults that were not present prior to implementation/maintenance activity [86].

Phase 6: Acceptance testing is typically performed by the end-user or a designated third party on a fully integrated system. During this phase, the end-user determines whether the system modification meets their requested needs and performs as expected [86].

Phase 7: The latest system version with the integrated modification request is made available to the end-user for daily use. During this phase, a system backup is created (prior to the integration of the modification request) and the latest system is installed alongside training at the customer facility [86].

It is evident that a communication channel with the end-user is important during the maintenance stage to communicate system issues and to acquire valuable feedback. A suitable communication channel should, therefore, be established in partnership with the end-user that allows for quick and effortless flow of information. Regular meetings should, therefore, be considered to report performance and address issues or required changes to the tools. Performance tracking in terms of key performance metrics, as outlined in Section 2.3, should be evaluated to establish the ongoing impact of the tools and to identify opportunities for further improvement.

This concludes the seven stages of the waterfall SDLC system/solution development methodology to be implemented in the development of the PF monitoring and reporting tools. A breakdown of the methodology with the steps involved at each stage is summarised in Figure 21.

Waterfall SDLC

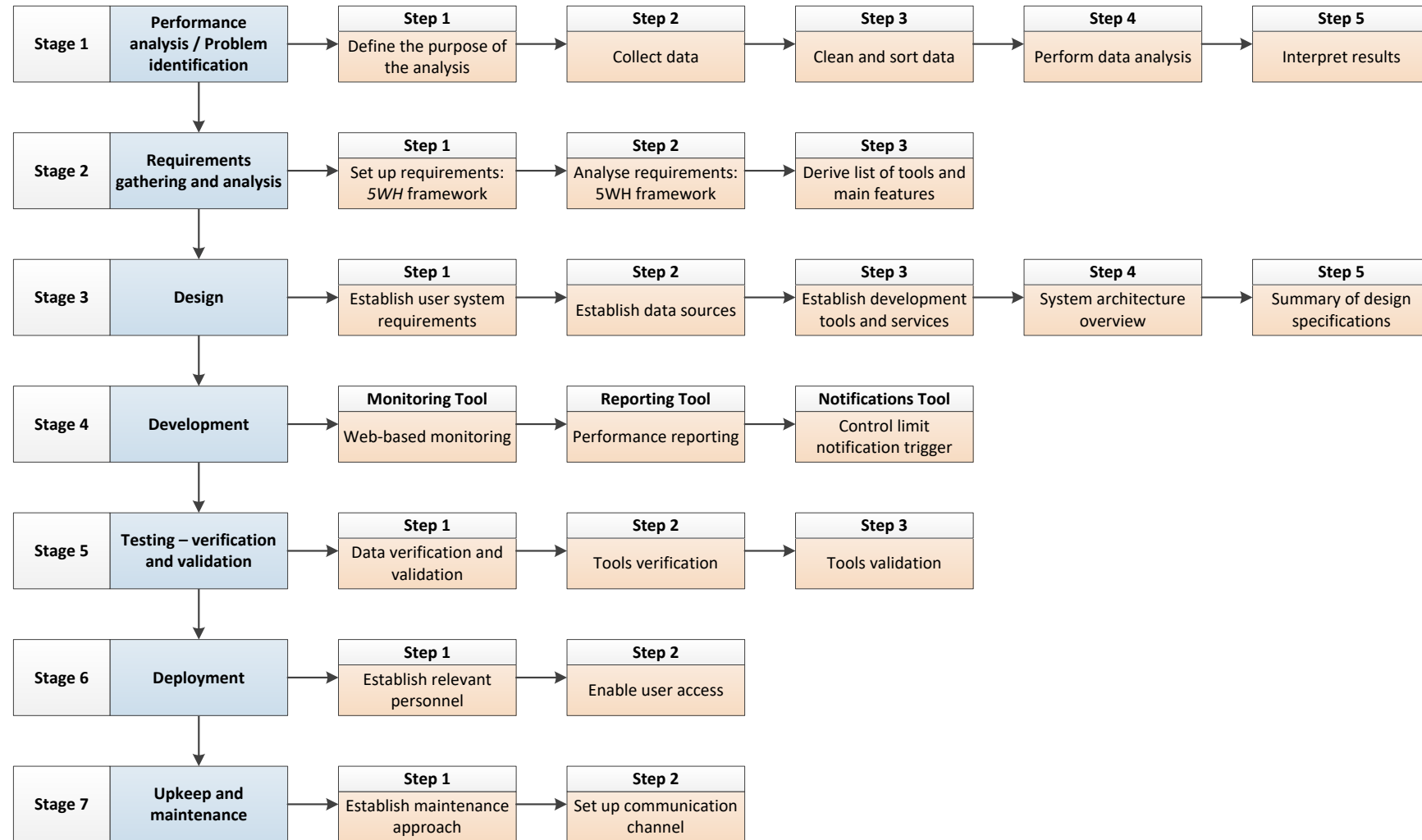


Figure 21: Waterfall SDLC methodology breakdown

2.9 Verification of the methodology

The methodology is verified for use by examining whether the criteria presented in the state of the art matrix, as shown in Table 2, is reflected within the methodology. Table 11 outlines where the criteria of the state of the art matrix is considered by the methodology.

Table 11: Verification of the methodology

Criteria	Methodology Stage						
	1	2	3	4	5	6	7
Power factor management	✓				✓	✓	✓
Monitoring		✓	✓	✓			
Performance reporting		✓	✓	✓			✓
Ranking and prioritisation	✓				✓		
Power factor correction	✓				✓		
Web-based tools			✓	✓			
Notifications		✓	✓	✓			
Mining	✓				✓	✓	✓

Table 11 indicates that all the criteria of the state of the art matrix were considered within the seven stages of the methodology.

2.10 Conclusion

This chapter details the waterfall SDLC methodology that can be utilised to develop the PF monitoring, reporting, and notification tools. This methodology provides a generic approach towards system/solution development and has a proven track record in various industries. It outlines the entire system/solution development life cycle from problem identification and requirements gathering to deployment and maintenance.

This method will be utilised to address the need for improved PFM on deep-level mines as outlined in Section 1.8. The various solutions and shortcomings identified from previous studies relating to PFM, as presented in Section 1.7, will be considered during implementation. Furthermore, the application of the methodology aims to achieve the objectives formulated in Section 1.9.

The following chapter applies the methodology to a relevant case study mine group where it is utilised to develop monitoring, reporting, and notification tools with the aim of improving PFM.

CHAPTER 3

3 METHODOLOGY IMPLEMENTATION AND RESULTS

3.1 Introduction

The waterfall SDLC methodology was proposed in Chapter 2 for the development of monitoring and reporting tools with the aim of improving PFM on deep-level mines. The seven stages of the methodology guide the development of the tools from problem identification and requirements gathering to deployment and maintenance.

In this chapter, the seven stages of the waterfall SDLC is applied to a real-world case study. The methodology aims to address the following objectives defined in Section 1.9 and derived from the background and shortcomings identified in previous literature as presented in Chapter 1:

- I. Establish the PF performance of various deep-level operation PODs.
- II. Rank and prioritise deep-level mine operation PODs for PF improvement based on power factors, demand charges, and reactive charges.
- III. Develop and implement PF monitoring, reporting, and notification tools:
 - a. Web-based monitoring and data visualisation of power factors.
 - b. Daily performance report on historic PF performance.
 - c. Notification system to warn personnel of poor power factors.
- IV. Develop and implement the tools by utilising existing platforms available to the deep-level mine operations.
- V. Reduce capacitor bank downtime by means of earlier fault detection.
- VI. Reduce annual penalties on reactive energy charges and demand charges.

3.2 Case Study

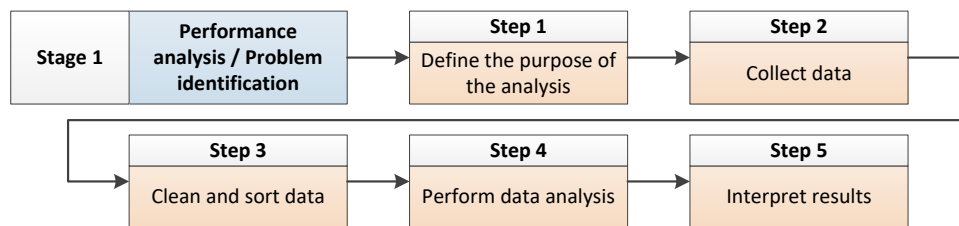
3.2.1 Case study background

The waterfall SDLC methodology presented in Chapter 2 was applied to a case study gold mine group to improve the PFM of various deep-level mine operations through monitoring and reporting. This gold mine group is situated in South Africa and consists of various deep-level mine shafts and gold processing plants.

As specified from the background in Section 1.3.3, penalties on excess reactive energy consumption are only applicable during the high-demand season (winter months). This study will focus on the impact of PFM on reactive energy charges and demand charges during the winter months for the case study mine group. Deep-level mine operations with PFC installed will be focused on for improved PFM.

For the purpose of this study, the various deep-level mine operations will be designated using placeholder names such as Operation A or Operation J to maintain confidentiality. The PODs of the respective operations will also be referred to with a placeholder name, for example the POD of Operation A will be referred to as POD A1. If an operation has more than one POD, it will be referred to as PODs B1 and B2, etc.

3.2.2 Stage 1: Performance analysis



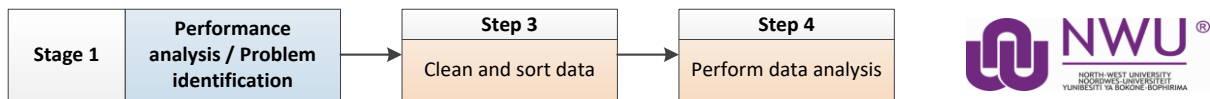
Step 1 of the five-step approach to performance analysis, as presented in Figure 17, is to define the purpose of the analysis. The purpose was derived from the objectives outlined in Section 1.9.

The focus of the performance analysis was to achieve Objectives I and II. The insights gathered from the results will then be used to assist in the development of the PF monitoring and reporting tools in partial fulfilment of Objectives III and IV. The performance metrics used to analyse the PF performance of the various operations are outlined in Table 12.

Table 12: Case study performance metrics for power factor analysis

Performance Metrics	
Metric	Unit of Measure
Power factor	Ratio
Excess reactive energy consumption	reactive kilovolt-ampere-hour [kVarh]
Reactive energy charge	Rand [R]
Maximum apparent power consumption	kilovolt-ampere [kVA]
Network demand charge	Rand [R]
Excess apparent power consumption	kilovolt-ampere [kVA]
Excess network demand charge	Rand [R]
Capacitor bank downtime	Hours [h]

Step 2 comprises collecting data based on the specified performance metrics in Table 12. The performance data was collected from internal and external data sources. The internal data sources were the mine operation's SCADA and the iST ecWin services utilised by the mine group, while the external data sources were the Eskom electricity bills of the respective deep-



level operation's PODs. Table 13 summarises the data sources used for the respective performance metrics.

Table 13: Case study performance metric data sources

Data Sources	
Performance Metric	Source
Power factor [Ratio]	SCADA & iST ecWin
Excess reactive energy usage [kVarh]	SCADA & iST ecWin & Eskom bills
Reactive energy charge [R]	Eskom bills
Maximum apparent power consumption [kVA]	SCADA & iST ecWin & Eskom bills
Network demand charge [R]	Eskom bills
Excess apparent power consumption [kVA]	Eskom bills
Excess network demand charge [R]	SCADA & iST ecWin & Eskom bills
Capacitor bank downtime [h]	SCADA & iST ecWin

Step 3 comprises cleaning and restructuring the data from the internal and external data sources to allow the performance analysis to take place. This involved the removal of duplicate data points and anomalous or erroneous data that could skew the analysis to ensure the data analysis results provide logical outputs.

In **step 4**, the data was analysed to determine the performance metrics of several deep-level mine operation PODs. The performance analysis focused on operations with capacitor banks installed and with PODs that follow the Eskom Mega Flex (non-local authority) tariff structure. As discussed in Section 1.3.3, this tariff structure is applicable to PODs with an NMD greater than 1 MVA.

The selection was further refined to only include operations that are positioned within a transmission zone of less than 300km and have a voltage supply between 500V and 66Kv. This was done to ensure the Eskom tariffs of the various operation PODs were consistent to prevent a distorted comparison of the financial impact of poor power factors on the network demand charges (apparent power consumption). The tariffs of the various transmission zones and voltage supplies are presented in Appendix C (Figure 79).

Subsequently, a sample size of nine deep-level mine operations were selected for the performance analysis with a total of 11 PODs. The operations with their respective PODs are presented in Table 14 in no particular order.

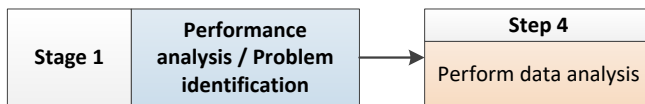


Table 14: Case study operation PODs

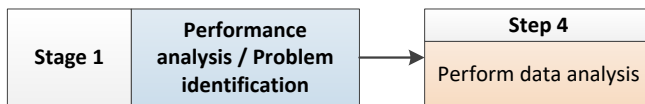
Deep-level Mine Operation PODs	
Operation	POD
A	A1
	A2
B	B1
	B2
C	C1
D	D1
E	E1
F	F1
G	G1
H	H1
I	I1

The PODs of these operations were analysed to establish their performance based on the designated performance metrics and data sources as presented in Table 13. The equations used to determine each performance metric are summarised in Table 15.

Table 15: Case study performance metric equations

Performance Metric Equations	
Metric	Applicable Equation
Power factor [Ratio]	$PF = \frac{P}{S}$
Excess reactive energy consumption [kVARh]	$Q_{Excess} = Q_{Total} - 0.3P_{Total}$
Reactive energy charge	$Reactive\ Energy\ Charge = Q_{Excess} * Eskom\ Tariff_{Excess\ reactive\ energy}$
Maximum apparent power consumption [kVA]	$S_{Max} = MAX(\sqrt{(P)^2 + (Q)^2})$
Network demand charge [R]	$Network\ Demand\ Charge = S_{Max} * Eskom\ tariff_{Network\ demand}$
Excess apparent power consumption [kVA]	$S_{Excess} = S_{Max} - P_{At\ max\ S}$
Excess network demand charge [R]	$Excess\ Network\ Demand\ Charge = S_{Excess} * Eskom\ tariff_{Network\ demand}$
Capacitor bank downtime [h]	*Estimated based on the power factor reduction period.

The excess reactive energy consumption, maximum apparent power consumption, and the network demand charges data were retrieved from the monthly Eskom electricity bills to



uphold the accuracy of the performance analysis. The remaining performance metrics are not available on the Eskom electricity bill and were, therefore, calculated based on the available data from internal sources (SCADA and iST ecWin).

The performance analysis investigated the PF performance during the high-demand season. As discussed in Section 1.3.3, the excess reactive energy is penalised on the Eskom bill from 1 June to 31 August. Due to the structure of the Eskom monthly billing periods, the penalties are recorded on the June to September Eskom electricity bills; therefore, the analysis period ranged from 18 May to 18 September 2021, as presented in Table 16.

Table 16: Case study Eskom billing periods (June to September)

Eskom Electricity Billing Period (June to September)	
Billing Month	Billing period
June	18 May – 16 June (16 June included)
July	17 June – 17 July (17 July included)
August	18 July – 17 August (17 August included)
September	18 August – 18 September (18 September included)

Table 17 and Table 18 provide a summary of the performance analysis conducted on the 11 PODs of the nine deep-level mine operations over the analysis period. Table 17 gives an overview of the PF performance and the resulting impact on excess reactive energy and maximum apparent power consumption.

Table 17: Case study power factor impact on reactive energy and apparent power consumption

Power Factor Performance Impact on kVArh and kVA (June – September 2021)						
Operation	POD	Average Power Factor	Excess Reactive Energy Consumption [kVArh]	Max Apparent Power Consumption [kVA]	Excess Apparent Power Consumption at Max Demand [kVA]	Estimated Capacitor Bank Downtime [h]
H	H1	0.75	7 004 204	17 643	6 519	4 113
F	F1	0.85	6 586 973	37 274	4 751	4 784
G	G1	0.90	2 356 078	19 378	3 675	1 988
C	C1	0.97	680 804	47 412	8 716	592
B	B2	0.92	633 601	8 726	128	653
A	A2	0.95	201 049	8 208	440	0
B	B1	0.96	58 512	9 092	604	0
I	I1	0.99	16 647	6 825	46	0
E	E1	0.98	14 571	21 128	638	0
A	A1	0.99	1 143	22 428	196	0
D	D1	0.99	0	17 894	6	0

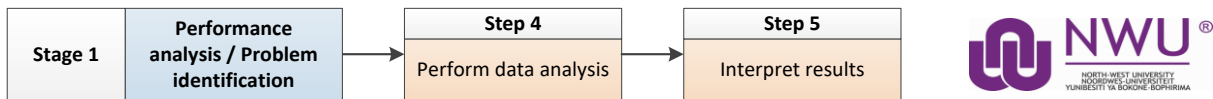


Table 18 outlines the financial impact of the PF performance on the reactive energy charges and network demand charges. Table 17 and Table 18 are ranked based on the total reactive energy consumption and total reactive energy charges respectively.

The excess reactive energy consumption and capacitor bank downtime values represent the total for each operation POD over the analysis period. The maximum apparent power consumption showcases the maximum kVA consumption measured during this period. The excess apparent power consumption was calculated at the maximum apparent power consumption reading of the POD as presented in Table 17.

Table 18: Case study power factor financial impact on reactive energy and demand charges

Power Factor Performance Impact on Electricity Costs (June – September 2021)						
Operation	POD	Average Power Factor	Total Reactive Energy Charge [R]	Total Network Demand Charge [R]	Total Excess Network Demand Charge [R]	Estimated Capacitor Bank Downtime [h]
H	H1	0.75	1 344 107	2 802 160	1 013 488	4 113
F	F1	0.85	1 264 040	6 049 024	786 028	4 784
G	G1	0.90	452 131	2 915 748	479 970	1 988
C	C1	0.97	130 646	7 528 560	503 123	592
B	B2	0.92	121 588	1 307 443	9 753	653
A	A2	0.95	38 581	1 318 788	66 813	0
B	B1	0.96	11 228	1 452 288	84 467	0
I	I1	0.99	3 195	1 123 643	7 883	0
E	E1	0.98	2 796	3 404 369	108 400	0
A	A1	0.99	219	3 600 706	28 559	0
D	D1	0.99	0	2 900 116	6 892	0

The electricity cost values presented in Table 18 were calculated based on the Eskom 2021/2022 tariffs, excluding VAT, as presented in Appendix C (Figure 79). The reactive energy charges were calculated at 19.19c/kWh. The total network demand charges and total excess network demand charges were calculated at R41.27/kVA/month. The total excess network demand charge was determined based on the excess apparent power consumption at the maximum demand (kVA) recorded during each respective month from June to September.

In **step 5**, the final step in the performance analysis, the performance metrics are interpreted to gather insight. This, in turn, will assist in the following phases of the SDLC to develop the monitoring, reporting, and notification tools. Figure 22 to Figure 26 visualise the results of the performance metrics and facilitate the evaluation thereof.

Figure 22 showcases the impact of the average PF on the excess reactive energy consumption of the various PODs.

As discussed in Section 1.3.3, excess reactive energy is recorded at a PF of 0.96 and less; therefore, the PF limit presented in the Figures 25, 26, and 29 is set to 0.96.

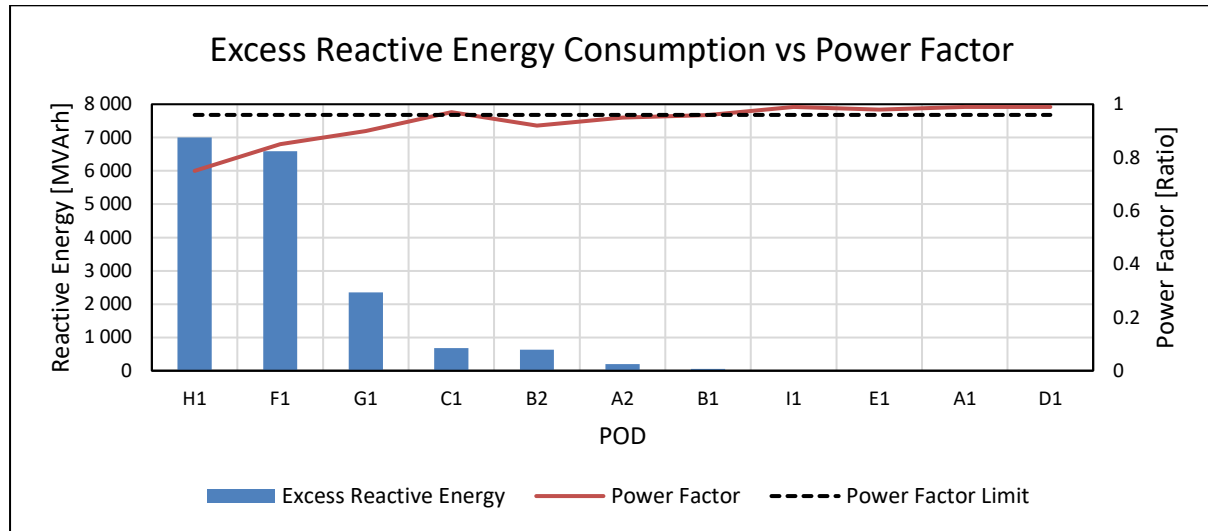


Figure 22: Case study power factor impact on excess reactive energy

It is evident from Figure 22 that the average PF has a considerable impact on the excess reactive energy consumption. PODs H1 and F1 had the highest excess reactive energy consumption (both exceeding 6 000 MVarh) and the lowest average power factors of 0.75 and 0.85 respectively. The third highest excess reactive energy consumer was POD G1 (2 000 MVarh) at an average PF of 0.90. A significant reduction in MVarh is visible as the average POD PF increases above 0.90 from POD C1 to D1.

The power factors of PODs B1, I1, E1, A1, and D1 ranged from 0.96 to 0.99 and consumed minimal excess reactive energy compared to PODs H1, F1, G1, C1 and B2. The exception is POD C1 with an average PF of 0.97, but with almost 12 times more excess reactive energy consumption than POD A2 at an average PF of 0.96. This large variation in the expected excess reactive energy consumption of POD C1 can be attributed to the size difference between the operations and the capacitor bank downtime.

Based on the maximum apparent power consumption in Figure 23, it is evident that Operation C is larger than Operation A when comparing POD C1 to A1 and A2 combined. It is also the largest case study operation being examined. Therefore, if the PF of POD C1 reduces below 0.96, the excess reactive energy consumption will be much higher than that of the other PODs at the same PF. Figure 24 showcases the difference in capacitor bank downtime between POD C1 and that of PODs A2 to D1. POD C1 had an estimated capacitor bank downtime of 592 hours, whilst PODs A2 to D1 had no recorded capacitor bank downtime.

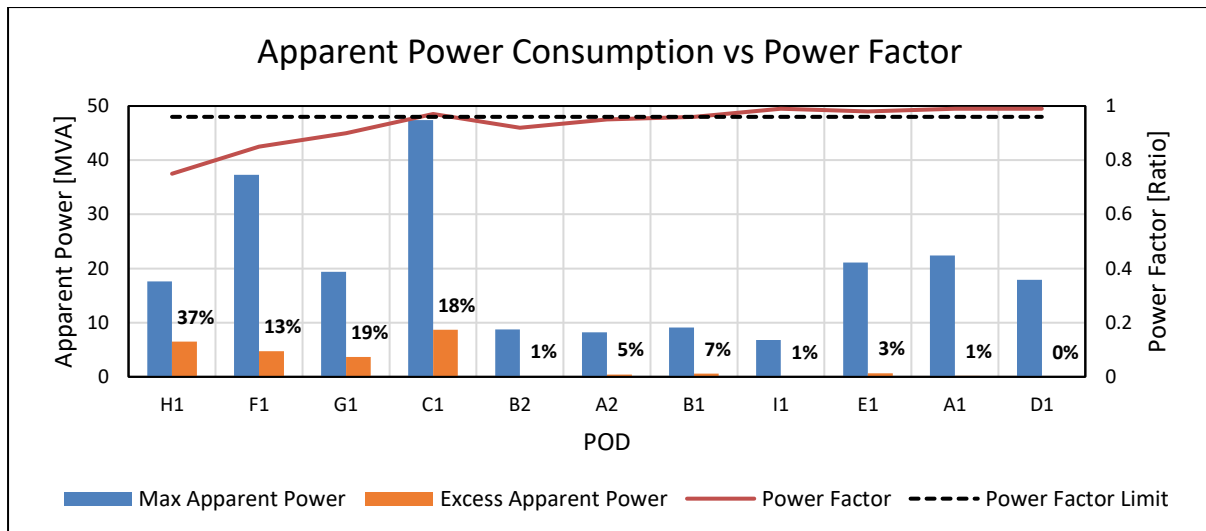


Figure 23: Case study power factor impact on apparent power consumption

Although the average PF of POD C1 was 0.97, the maximum kVA consumption was measured during a capacitor bank downtime period at a PF of 0.82. This led to the estimated excess consumption of 8 716 kVA at the maximum demand reading of 47 412 kVA. This highlights the importance of minimising capacitor bank downtime to mitigate its impact on demand charges and not only on reactive energy charges.

The relationship between capacitor bank downtime and excess apparent power consumption can be seen when comparing Figure 23 and Figure 24. All the PODs with capacitor bank downtime had an excess apparent power consumption above 10% except for POD B2 at only 1%, as the maximum kVA consumption recorded between June and September of POD B2 was not measured during the capacitor bank downtime. The maximum kVA was recorded during a period of increased demand at a PF of 0.98.

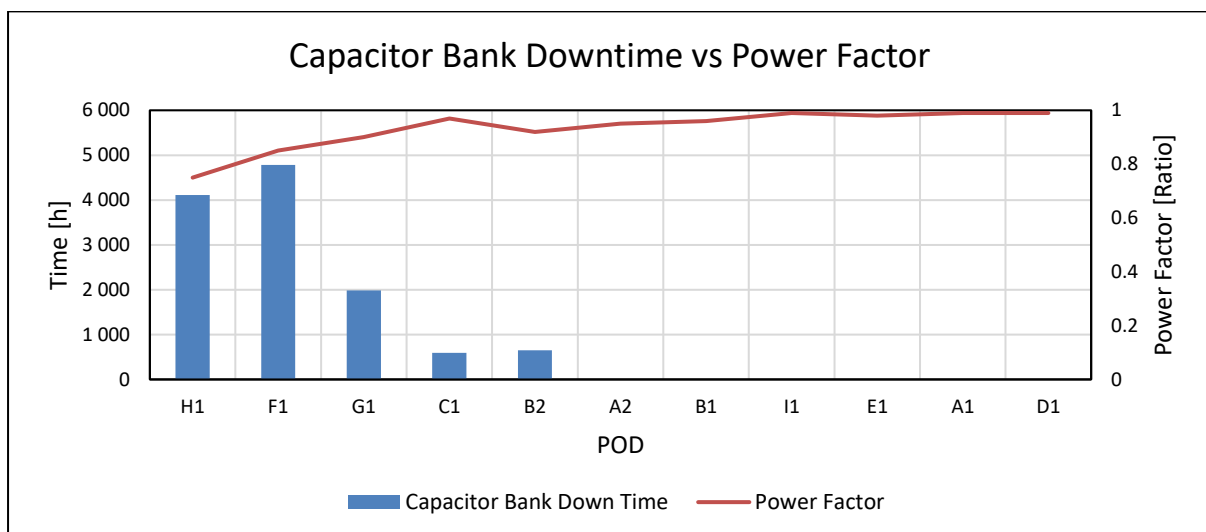
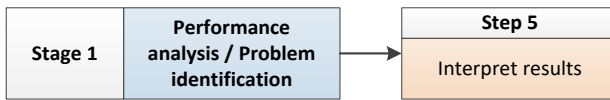


Figure 24: Case study capacitor bank downtime impact on power factor



In Figure 24 and Figure 25, the link between the capacitor bank downtime, PF, and excess reactive energy consumption are illustrated. As the capacitor bank downtime increased, the average PF decreased (Figure 24) and the excess reactive energy increased (Figure 25).

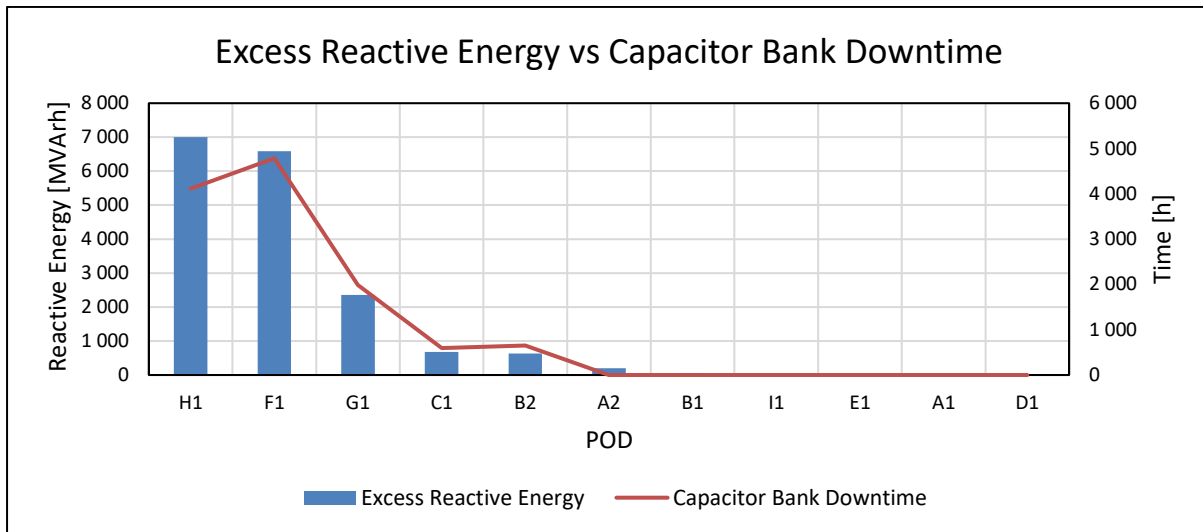


Figure 25: Case study capacitor bank downtime impact on excess reactive energy consumption

It should be noted that POD F1 had a higher estimated capacitor bank downtime than POD H1, but POD H1 had a higher excess reactive energy consumption. This anomaly may be attributed to the higher average PF of POD F1 (0.85) compared to POD H1 (0.75).

Although the maximum kVA recorded for POD F1 (37 274 kVA) was much higher than H1 (17 643 kVA), the excess reactive energy consumption of POD H1 is still higher. This can be confirmed by using Equation 3 to determine the total reactive energy, Equation 15 to determine the non-excess reactive energy, and Equation 16 to determine the excess reactive energy over the analysis period.

The average reactive energy at an average PF of 0.75 for POD H1 is 10 575 kVarh, with an average excess reactive energy of 6 965 kVarh. Similarly, for POD F1, the average reactive energy at an average PF of 0.85 is 13 511 kVarh, with an average excess reactive energy of 6 286 kVarh. This equates to POD H1 having, on average, approximately 10% more excess kVarh consumption than POD F1, although POD F1 is a much larger consumer in terms of kVA consumption. Thus, it is possible for H1 to have a higher total excess kVarh consumption than F1 between June and September. This also indicates inefficiencies in the electrical system at H1 due to the low PF readings with the absence of PFC.

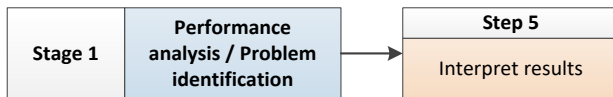


Figure 26 provides an overview of the estimated cost impact of the PF performance of the various PODs.

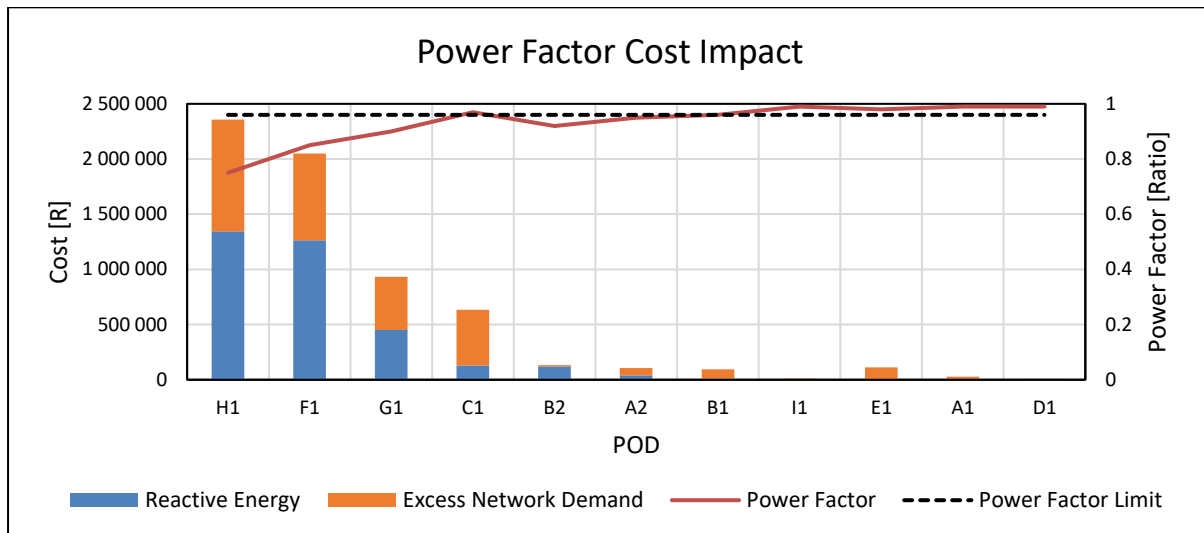


Figure 26: Case study power factor cost impact

The reactive energy and excess demand costs decreased as the average PF of the POD increased. The PF performance of PODs B2, A2, B1, I1, E1, A1, and D1 amounted to a total cost impact of less than R0.2 million respectively, with the average PF ranging from 0.95 to 0.99. Both PODs C1 and G1 had a total cost impact of between R0.5 million and R1 million, with capacitor bank downtimes of over 500 hours. PODs F1 and H1 saw the largest cost impact of R2.05 million and R2.35 million respectively, resulting from both PODs having capacitor bank downtimes exceeding 4 000 hours at their respective incomers.

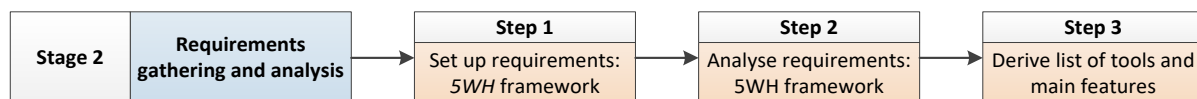
During the analysis period, the cost impact of the excess reactive energy (kVArh) on the 11 PODs amounted to over R3.36 million and R3.09 million in excess network demand (kVA) charges. This equates to a total cost impact of over R6.45 million, of which R6.1 million can be attributed to the PODs that experienced capacitor bank downtime (H1, F1, G1, C1, and B2). Based on the aforementioned PODs, H1, F1, G1, C1, and B2 are in need of improved PFM; however, it is crucial to maintain the PF performance of the other PODs (A2, B1, I1, E1, A1, and D1) to minimise capacitor bank downtime when it occurs.

No active daily monitoring, reporting, or notification tools were implemented to manage the power factors. As a result, poor power factors were mostly identified when the reactive energy charges on a POD were inspected on the Eskom electricity bill, which led to frequent and prolonged periods of capacitor bank downtime.

Apart from the lack of PF monitoring and reporting, some of the deep-level mining operations were identified as having outdated PFC systems, such as POD F1 and H1. The PFC not being updated as the electrical system expanded and the demand increased contributes to this. This does not form part of the study but will need to be addressed in the future to further enhance the PF performance of certain operations. However, the implementation of monitoring and reporting tools could potentially assist in identifying these operations.

Considering the aforementioned factors, the total reactive energy charges of the case study mine group was over R16.96 million during the 2021 analysis period, confirming the need for improved PFM. The insights gathered from carrying out the performance analysis will assist in the development and implementation of PF monitoring, reporting, and notification tools to achieve Objectives III and IV.

3.2.3 Stage 2: Requirements gathering and analysis



The *5WH* framework, outlined in Figure 18, was employed during the requirements gathering and analysis stage to process the insights gathered from the performance analysis. As discussed in Section 2.3.1, the *5W* questions were implemented to define the requirements of the PFM tools, while the *H* question was used during the analysis of the requirements to establish the list of tools and their respective features to be designed and developed.

3.2.3.1 Requirements gathering

The *5W* questions utilised to process the problem and establish the requirements of the tools are outlined in Table 19. The answers of the *5W* questions were used to define the requirements with the resulting requirements presented in Table 20. The subsequent list of requirements was then used to establish the tools and features to be designed and developed through the requirements analysis phase.

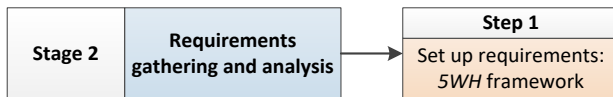


Table 19: Case study requirements gathering through 5W questions

5W Questions and Answers	
Who?	
Question(s)	Who will be using the PF tools?
Answer(s)	Relevant site personnel concerned with energy management.
What?	
Question(s)	What type of tools are required?
Answer(s)	PF monitoring, reporting, and notification tools.
When?	
Question(s)	When will the tools be used?
Answer(s)	The tools will be used daily.
Where?	
Question(s)	Where will the tools be accessed?
Answer(s)	The tools will be accessed onsite and remotely.
Why?	
Question(s)	Why is it required to develop these tools?
Answer(s)	The need exists to improve PFM on deep-level mine operations, along with opportunities to reduce electricity costs on the monthly Eskom bill.

Table 20: Case study list of requirements

List of Requirements	
5W	Requirements
Who	Personnel concerned with energy management must have access to the PF tools.
What	- The following PF tools must be available: - Monitoring and data visualisation. - Daily performance reporting. - Notification system.
When	Users must be able to access the tools at any time.
Where	Users must be able to access the tools onsite and remotely.
Why	- The tools must be able to assist in: - Improving PFM on deep-level mines. - Enable energy cost savings on the Eskom electricity bill.



3.2.3.2 Requirements analysis

The “How?” question of the 5WH approach was used to analyse the requirements listed in Table 20. The analysis of these requirements is presented in Table 21.

Table 21: Case study requirements analysis

Requirements Analysis	
Requirements	Analysis (H – How?)
Personnel concerned with energy management must have access to the PF tools.	Relevant staff will have access via the web-based energy management platform already accessible.
PF monitoring and data visualisation tool.	Users will be able to monitor the current PF performance of the various operations based on the lowest data extraction frequency available. Historic data visualisation and data extraction for independent analysis will also be on offer.
Daily PF performance reporting tool.	Users will have access to a daily performance report via email. This will offer an overview of the daily and historic PF performance of the various operations.
PF notification tool.	Users will be notified of variations in PF performance via a mobile application or SMS based on set control limits.
Users must be able to access the tools at any time.	The tools and services will be continuously accessible online by means of an internet browser.
Users must be able to access the tools onsite and remotely.	Users will have onsite and remote access via a smartphone or computer with a web browser installed (internet access is required).
The tools must be able to assist in improving PFM on deep-level mine operations.	The tools will assist users to improve the management of their power factors by keeping them informed and enabling pro-active measures to be taken when issues arise. This will be achieved by facilitating the identification of operations with poor power factors to be investigated for improved performance: (1) Identify capacitor banks that are inactive or faulty. (2) Identify outdated PFC that need to be updated.
The tools must be able to assist in achieving energy cost savings on the Eskom electricity bill.	The tools will assist in reducing the Eskom electricity bill by potentially minimising capacitor bank downtime via earlier fault detection (variations in PF performance) and identifying opportunities to improve outdated PFC which could result in reduced reactive energy penalties during the high-demand season and reduce the apparent power consumption which is billed monthly.



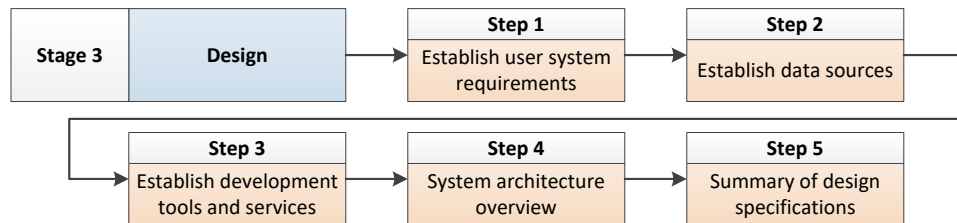
The list of tools and their respective features were derived from the requirements analysis, taking the background, literature, and performance metrics into account. Table 22 outlines the features of the respective tools.

Table 22: Case study list of tools and features

List of Tools and Features	
Tools	Features
Monitoring	• Display current PF performance value (updated based on the lowest available data extraction frequency – every 30 minutes). • Sort sites within the same billing district in alphabetical order or according to current POD PF performance. • Colour code POD PF values: ◦ Green – indicates a PF above 0.96. ◦ Red – indicates a PF below 0.96. • Indicate data loss. • Provide the option to visualise daily (24 hour) and historic (period selection) PF performance of a POD's individual incomers. • Inspect data points on the PF profiles. Indicate data point date and time as well as PF value. • Provide the option to export the data of the PF profiles in the .xlsx and .csv file formats for further independent analysis.
Reporting	• Provide a daily and historic table summary of the POD performance of the various operations to include the following performance indicators: ◦ Excess reactive energy ◦ Maximum demand ◦ Maximum excess demand ◦ NMD ◦ Average PF • Colour code the PF performance in the tables: ◦ Green – indicates a PF above 0.96. ◦ Orange – indicates a PF below 0.96 and equal to/above 0.90. ◦ Red – indicates a PF below 0.90. • Highlight the maximum demand value in red if it exceeds the NMD. • Rank tables according to excess kVarh consumption (highest to lowest). • Show daily and historic POD power performance graphs of the various operations. The profiles should include the following data profiles: ◦ Active power ◦ Reactive power ◦ Apparent power ◦ POD PF and Eskom PF limit • Compile and distribute the report automatically to the email addresses of the relevant personnel daily.
Notification	• Adjustable alarm trigger (adjust PF limits and alarm trigger frequency). • Smartphone integration: ◦ Send in-application notice to personnel when an alarm is triggered. ◦ Option to inform personnel via SMS. ◦ Indicate operation POD name and PF performance on notification. ◦ View notification history.

This concludes the requirements gathering and analysis stage. The list of features for the respective tools were considered during the design stage where the approach towards developing these tools is defined.

3.2.4 Stage 3: Design



The approach used to develop the PFM tools and features was defined during the design stage to satisfy the requirements outlined in stage 2. As discussed in Section 2.4, the design stage was divided into four main design categories for each tool:

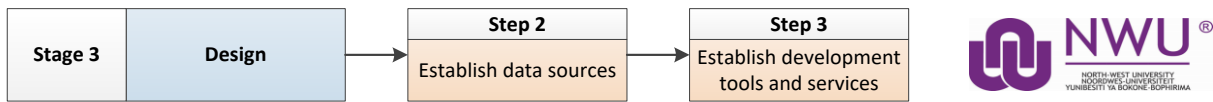
1. User system requirements
2. Data sources
3. Services or software products (to be employed for development)
4. System architecture

These design categories represent the design specifications for the PF tools to be developed.

User system requirements: As discussed in Section 2.4, the system requirements refer to the hardware and software configuration a system must have for a software application to run effectively on the installed device. All three PF tools were designed to be used on low hardware specification devices with internet connectivity and the ability to run a web-browser. These hardware requirements are crucial for the user to access and utilise the PF tools remotely.

However, for the notification system, it is recommended to utilise a cellular device such as a smartphone or tablet for optimal performance. The notification system was primarily designed to be used by cellular devices, as they are compact and convenient to carry around. This allows the user to receive notifications via a mobile application or SMS and to be informed regarding poor PF performance in the absence of a personal computer.

The PF monitoring and reporting tools require an installed operating system such as Microsoft Windows with the addition of a web-browser such as Google Chrome. An operating system such as Google Android (version 5.1 and up) is recommended for cellular devices to be compatible with the notification tool.



Data sources: The availability of trusted data sources is integral to the functionality of the tools. Therefore, the primary data sources selected were the iST ecWin and the mine operation SCADA. These sources are trusted by the mine operation personnel and utilised daily via the existing infrastructure. Furthermore, these data sources are capable of 30-minute data extraction intervals and log the average data reading for every 30-minute period.

This enables the web-based monitoring and data visualisation tool to display the latest PF performance of an operation POD every 30 minutes and the notification tool to analyse the data every 30 minutes for a potential notification trigger. This also supports daily data visualisation profiles with 48 data points which can assist in identifying changes in the POD PF when examined on the monitoring tool and data visualisation tool.

Services/software products utilised and software development tools: The requirements and features listed in stage 2 were considered during the selection of the software products and development tools to be used. The use of software platforms already available to the mine operations were also prioritised, in partial fulfilment of Objective IV, to minimise the development and implementation costs of the tools. The software products selected for the development and implementation of the tools were:

- Microsoft Power BI
- Management Toolbox (MTB)
- Admin Toolbox (ATB)
- Reporting Toolbox (RTB)
- Process Toolbox (PTB)
- ASTIR

Microsoft Power BI is a business analytics service used to visualise data and share insights by enabling users to construct interactive dashboards. Data from various supported local and cloud-based sources can be accessed and utilised by Power BI such as:

- Databases (IBM databases, SQL Server Database and Google BigQuery)
- Files (PDF, Excel, SharePoint, and XML)
- Online services (Salesforce, Google Analytics, Adobe Analytics, and Dynamic 365)

The Power BI Desktop application is used to generate interactive dashboards on a personal computer, whilst Power BI Services is used to publish the dashboards to the cloud to enable remote online access. The dashboards created in Power BI Desktop can be embedded into



existing applications or websites and the data is always kept up to date via automated, incremental refreshes⁶⁸.

Microsoft Power BI was selected for the development of the web-based monitoring and data visualisation tool due to its ability to create data visualisations and interactive dashboards. It is free to download and compatible with various file formats and data sources.

Furthermore, it can be embedded into existing web applications such as Management Toolbox (MTB) which is already accessible to the case study deep-level mine operations. Therefore, MTB was selected as the platform upon which these PF tools were built due to its accessibility and the case study mine groups familiarity with the application.

MTB is a data monitoring and logging application primarily used to monitor and log meter readings as well as other systems data on South African mining operations⁶⁹. It also provides users with specialised tools and reporting capabilities. It is available in the form of a web application which can be accessed via a web-browser or as a mobile application which can be installed on cellular devices such as smartphones or tablets.

The MTB web application is used to host the PF monitoring and data visualisation tool as well as the notification system. Process Toolbox (PTB) was selected for the development of the notification system due to its integration with MTB (web- and mobile application). PTB is a system simulation and optimisation tool used to design, analyse, and optimise system performance [75].

PTB has access to the iST data tags and the mine operation's SCADA which can be used to set up limits based on the data it receives. The MTB mobile application can be used to send in-application notifications based on the PF limits created in PTB, with the option to view the historic notifications received. PTB also supports SMS messages that can be sent to cellular devices.

Reporting Toolbox (RTB) was selected for the development of the PF report to be sent out daily to relevant personnel across various deep-level mine operations. RTB is used for generating PDF reports based on data tags. It has built-in formatting, layout, and style settings which ensures consistency across various reports. Moreover, it provides built-in and custom calculations that can be used within the report.

⁶⁸ Microsoft, 'Power BI Desktop-Interactive Reports', 2019. <https://powerbi.microsoft.com/en-us/desktop/> (accessed Jan. 12, 2023).

⁶⁹ MCI (Pty) Ltd., 'Management Toolbox', 2023. <https://play.google.com/store/apps/details?id=eta.management.toolbox> (accessed Aug. 08, 2023).



ASTIR is a software product used to translate the system data of the case study mine group and store the data in a database. This data is then used for data transfer or reporting purposes. ASTIR is compatible with the data file formats from iST and the CSV files received from the mine operation SCADA. The data stored by the ASTIR database is used by RTB, PTB, Microsoft Power BI, and is transferred to the MTB database where it enables the specialised tools on offer.

Admin Toolbox (ATB) is a web application that links ASTIR and MTB. ATB provides an administrative interface to view and export data, configure data handling, and distribute reports based on the data from the ASTIR database.

It is integrated with ASTIR, MTB, RTB, and PTB and is used to:

- Transfer data between the ASTIR database and the MTB database.
- Link data to the Microsoft Power BI PF monitoring and data visualisation tool.
- Link the monitoring tool to MTB where it is hosted for user access.
- Provide the PTB notification tool with data.
- Link the notification tool to MTB for user access.
- Access RTB for report creation and automate report distribution.

These software services/products work together in an ecosystem, which eases the implementation of the tools due to the existing integration. No software development tools were selected for the development of the PF tools. This was done in correspondence with Objective IV to ensure the tools were available on existing platforms accessible to the deep-level mine operations as well as minimising potential issues with software integration, installation, and accessibility.

System architecture: The system architecture presented by Maheepala et al. [56] and the system documentation of the various software products were consulted to create a high-level overview of the system architectures of the three PF tools. This overview provides a summary of how the various components of the tool are linked to provide the user with the final output. These system overviews are presented in Figure 27 to Figure 29.

The system architecture of the web-based monitoring and data visualisation tool is depicted in Figure 27. As previously discussed, all three tools utilise iST ecWin and the SCADA of a mine operation as its data inputs. These inputs are translated and stored in the ASTIR database from where they are accessed by ATB to extract or link the data for further use. ATB can also be used to create new data tags that can be stored on ASTIR.

The input data stored on ASTIR is linked to the Power BI dashboard via ATB and hosted on MTB. ATB is used to create the link between the Power BI dashboard and the MTB web application to enable hosting. MTB is the interface used by the end user to access the Power BI dashboard (monitoring and data visualisation tool).

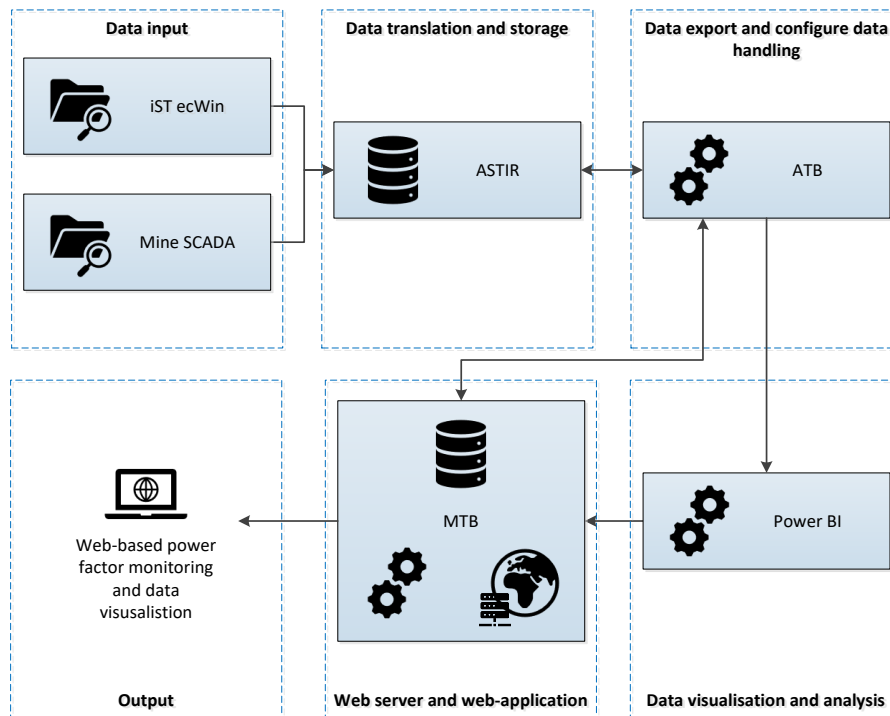


Figure 27: System architecture of the web-based power factor monitoring and data visualisation tool

As referred to previously, MTB has its own database for storing selective data for the various specialised tools it offers. ATB interface is used to transfer data between the ASTIR database and the MTB database. User access to the MTB web application is also managed by ATB.

The system architecture of the daily performance report is presented in Figure 28.

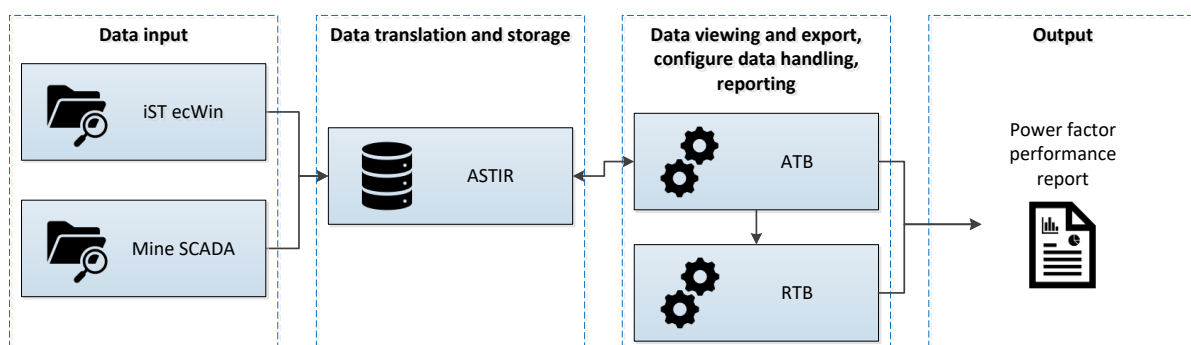


Figure 28: System architecture of the power factor daily performance reporting tool

RTB is accessed via the ATB interface to create the daily performance report. The data used by the RTB report is acquired from the ASTIR database via ATB. ATB manages the recipient list (email addresses) and the automation of the report distribution.

The system architecture of the notification system is presented in Figure 29.

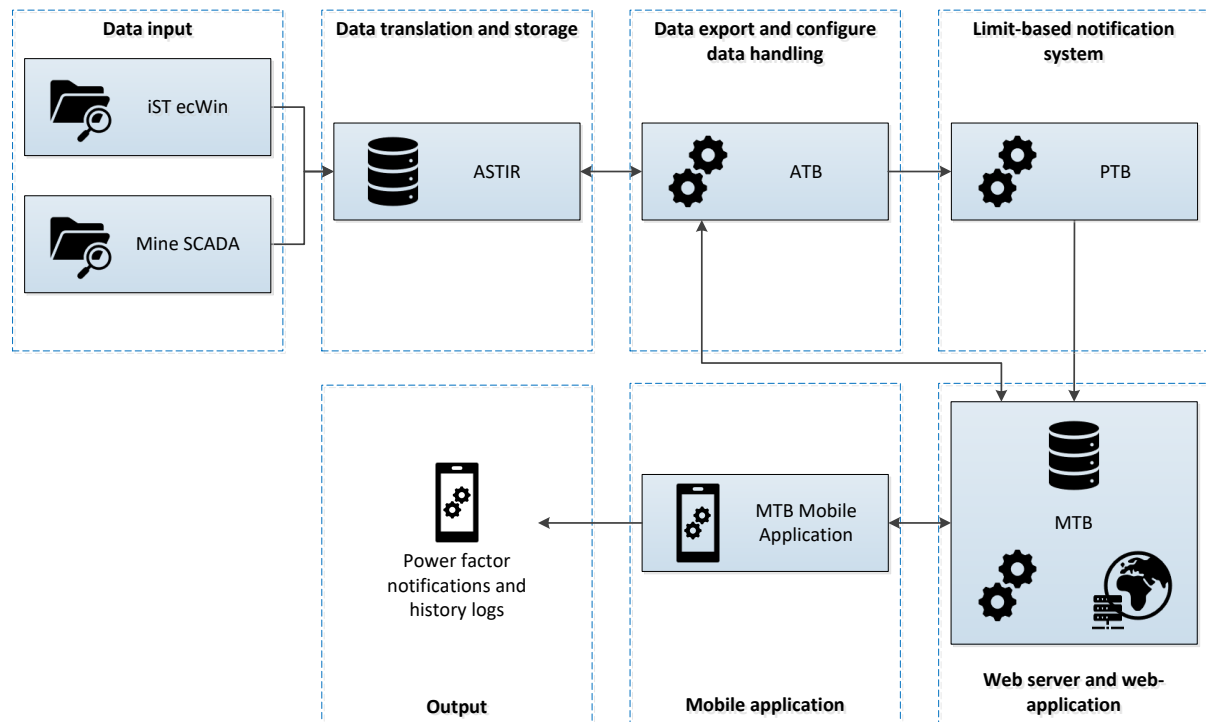


Figure 29: System architecture of the power factor notification system

The PTB notification system acquires data from the ASTIR database via ATB and is linked to the MTB web application using the ATB interface. The MTB mobile application is used to notify the end user when the PTB limits have been exceeded. Access to the MTB mobile application as well as the contact list for SMS distribution to end users is managed by ATB.

A holistic system architecture was compiled to showcase the integration of the software products used to develop the three PF tools. The integrated system architecture is presented in Figure 30.

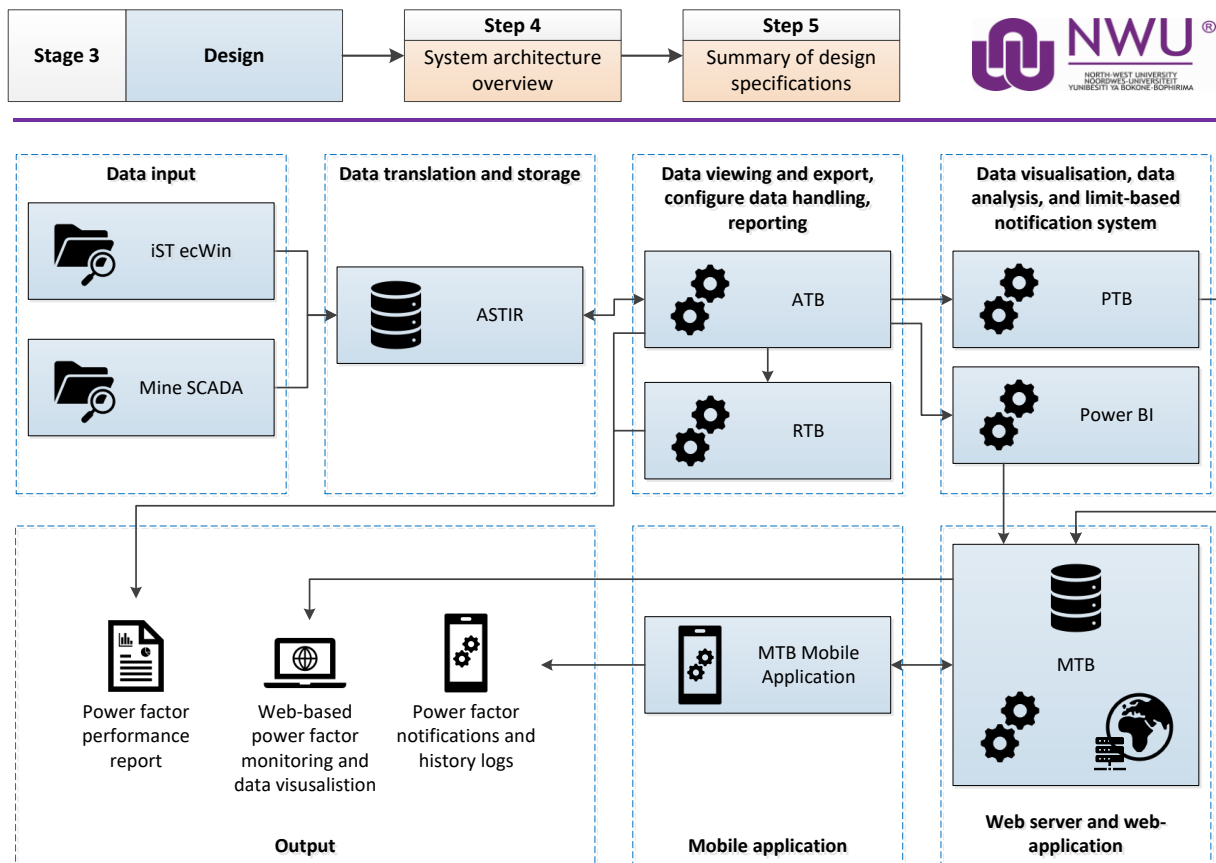


Figure 30: Integrated system architecture of the power factor tools

Design specification overview: The high-level design specifications, based on the four main categories discussed above, for the monitoring, reporting, and notification tools are outlined in Table 23 to Table 25.

Table 23: Web-based monitoring and data visualisation tool design specifications

Web-based Monitoring and Data Visualisation – Design Specifications		
Category	Specifications	
User system requirement	Hardware	Low hardware specification device with internet connectivity and the ability to run web-browser.
	Software	Operating system such as Microsoft Windows and browser software such as Google Chrome.
Data source(s)	- iST ecWin - SCADA	
Software product(s) and development tool(s)	- Microsoft Power BI - Admin Toolbox (ATB) - Management Toolbox (MTB) - ASTIR	
System architecture	Refer to Figure 27.	



Table 24: Daily performance reporting design specifications

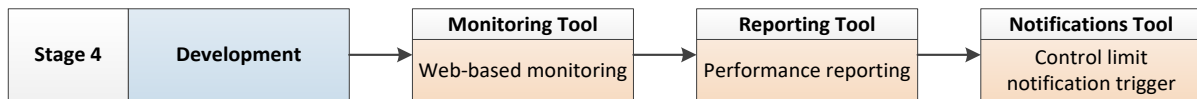
Daily Performance Report – Design Specifications		
Category	Specifications	
User system requirement	Hardware	Low hardware specification device with internet connectivity and the ability to run web-browser.
	Software	Operating system such as Microsoft Windows and browser software such as Google Chrome.
Data source(s)	- iST ecWin - SCADA	
Software product(s) and development tool(s)	- Reporting Toolbox (RTB) - Admin Toolbox (ATB) - ASTIR	
System architecture	Refer to Figure 28.	

Table 25: Notification system design specifications

Notification System – Design Specifications		
Category	Specifications	
User system requirement	Hardware	Low hardware specification device with internet connectivity and the ability to run web-browser. A smartphone or tablet device is recommended.
	Software	Operating system such as Google Android 5.1 and up.
Data source(s)	- iST ecWin - SCADA	
Software product(s) and development tool(s)	- Process Toolbox (PTB) - Admin Toolbox (ATB) - Management Toolbox (MTB) – Web and Mobile Application - ASTIR	
System architecture	Refer to Figure 29.	

This concludes the design stage. The design specifications, along with the requirements established in stage 2, enabled the transition to the development stage where the PF tools were developed.

3.2.5 Stage 4: Development



The PF monitoring, reporting, and notification tools were developed during this stage based on the designated features and design specifications as outlined in stages 2 and 3. The goal of this stage was to convert the design concepts into working products that address the documented requirements, in partial fulfilment of Objectives III and IV.

An overview of each PF tool developed is provided along with their respective features. The features of the tools are outlined in Table 22 as presented in Section 3.2.2. The mine operation POD names are censored in this section to ensure confidentiality.

Web-based monitoring and data visualisation

As discussed in the design stage, the web-based PF monitoring and data visualisation tool was developed using Microsoft Power BI. The Power BI dashboard is hosted on the MTB web-application. Figure 31 showcases the home page of the monitoring and data visualisation tool when accessed by the user on MTB.



Figure 31: Power factor monitoring and data visualisation dashboard home page

All the case study mine group PODs were incorporated into the home page to enable the user to view the latest POD PF performance of all the operations concurrently. The green blocks indicate the billing district to which the operation POD is allocated. The orange blocks



represent the POD names of the operations with their respective PF performance displayed to the right.

The PODs (site names) can be sorted in ascending or descending alphabetical order by clicking on the “Site name” label. The PODs can also be sorted based on the latest PF performance value in ascending or descending order by clicking on the “POD power factor” label. The PODs presented in Figure 31 are sorted in descending order based on the PF values.

The PF values are updated every 30 minutes via data from iST ecWin and the mine operation SCADA. Additionally, the values are colour coded based on the colour legend presented in the bottom left corner:

- Green indicates a PF value above 0.96.
- Red indicates a PF value below 0.96.

Data loss is indicated by the “Missing data” label displayed in pink.

A dropdown list is available in the top right corner below the “Select a site to further analyse” label, as showcased on Figure 32. A POD can be selected from the dropdown list to further analyse the PF performance.

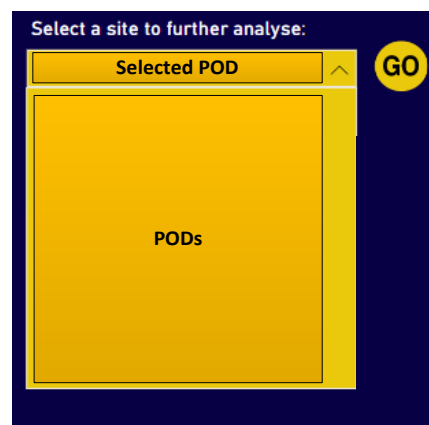


Figure 32: Dropdown list for further analysis of the selected POD

Once the POD has been selected, the “GO” button can be pressed to navigate the user to the analysis page. The PF analysis page is presented in Figure 33.

The PF analysis page provides an overview of the PF performance of the various incomers of the selected POD. The POD selected in Figure 33 has four incomers that can be reviewed in terms of their PF performance. Most incomers have a dedicated capacitor bank installed to manage the power factors of the connected equipment. The ability to view the PF performance



of the individual incomers can be helpful when attempting to identify the problem area which led to a reduced POD PF value.

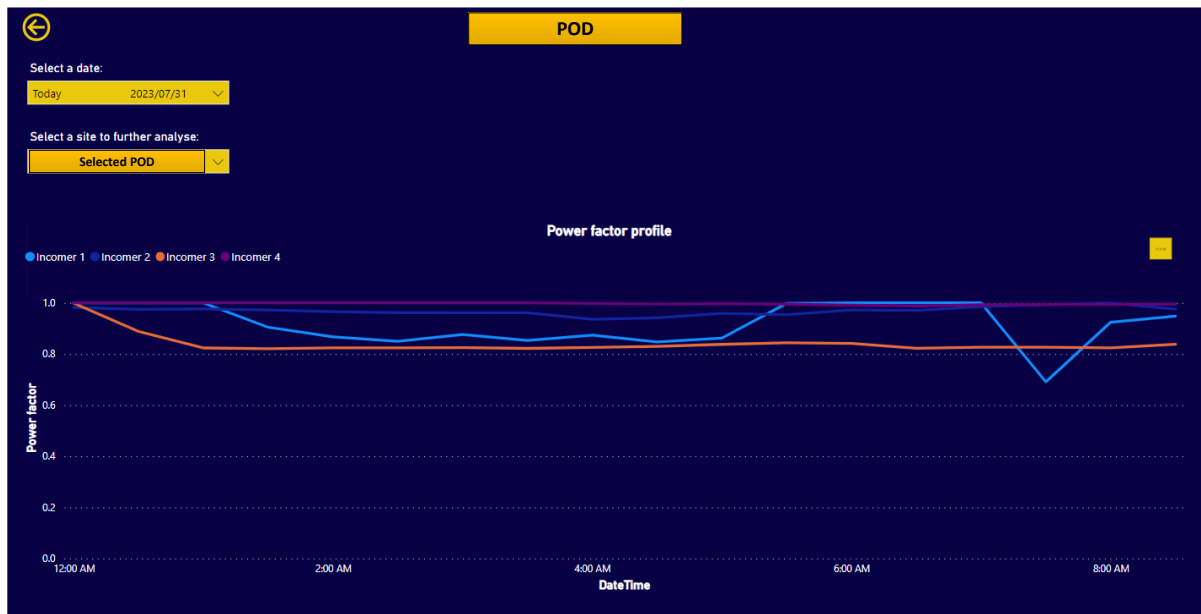


Figure 33: Power factor analysis page

The y-axis of the data visualisation presented shows the PF value and the x-axis the corresponding time at which the average PF value was recorded (based on 30-minute data intervals). Data points can be inspected by hovering the mouse over the data point.

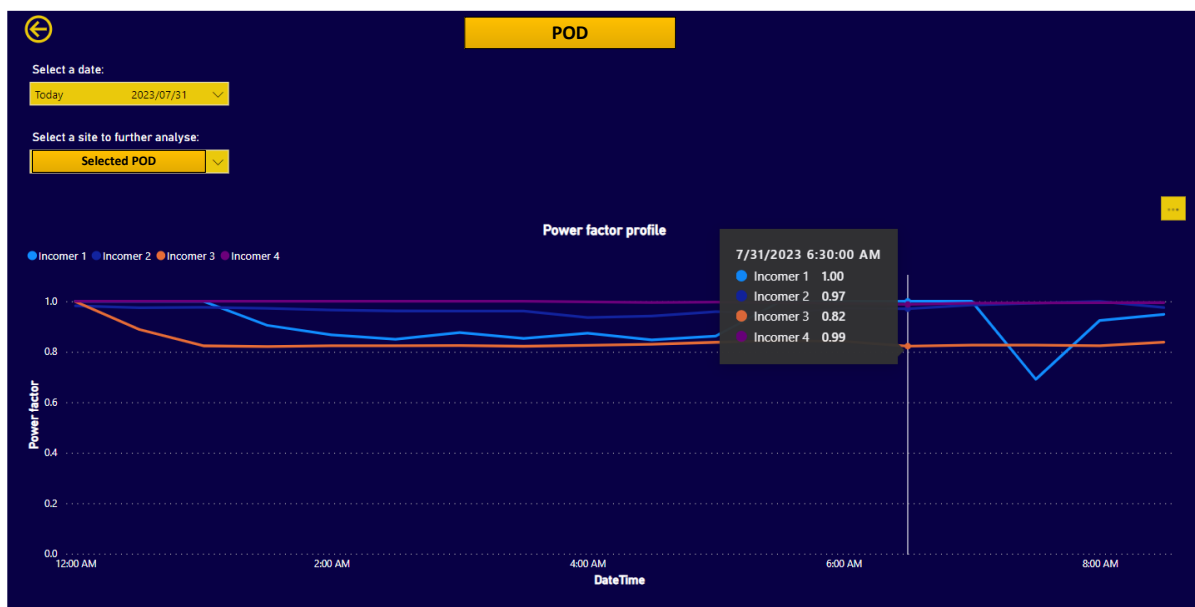


Figure 34: Data point inspection on power factor profile

The PF profiles presented in Figure 33 and Figure 34 are set to show the current day's performance, based on the latest available data, as indicated by the "Today 2023/07/31" selection in the top left corner.



Figure 35 highlights the period selection and POD selection dropdown lists available in the top left corner as presented in Figure 33 and Figure 34.

Figure 35: Period selection and POD selection dropdown lists

The following data viewing options are available in the period selection dropdown list:

- “Today” – current day / latest performance.
- “Yesterday” – previous day’s performance.
- “This Month” – current month’s performance including today.
 - i.e., 01 July to 14 July if today is the 15 of July.
- “Last 7 Days” – previous 7 day’s performance including today.
- “Last 14 Days” – previous 14 day’s performance including today.
- “Last 32 Days” – last 32 day’s performance including today.

Figure 36 showcases these options, as shown to the user, when the period selection dropdown list is selected.

Figure 36: Period selection dropdown list options

The PF profile, as shown in Figure 33 and Figure 34, will update based on the period selected from the period selection dropdown list in Figure 36.

The POD selected for further analysis can be changed by selecting another POD via the POD selection dropdown list below the period selection dropdown list as shown in Figure 35.



The data of the PF profiles can be exported by selecting the option menu located in the top right corner. The data extraction option is provided at the top of the dropdown list as shown in Figure 37.



Figure 37: Power factor profile options menu

Data can be extracted in the form of an .xlsx or .csv file as presented in Figure 38.

Figure 38: Data extraction options

Additionally, there is the option to view the data of the PF profiles in the form of a table and sort the legends of the profiles in ascending or descending order. These options are presented in the dropdown list as shown in Figure 37.

The PF monitoring and data visualisation tool can be useful to monitor changes on the PF performance on a daily basis, every 30 minutes. This can potentially assist users to swiftly



identify the impact of system changes on the PF performance of an incomer and the operation POD.

Daily performance reporting

The PF daily report was created using RTB. The report is distributed daily and was automated with ATB. The report contains an index with hyperlinks to allow for swift navigation between the main sections.

The two main sections of the report are:

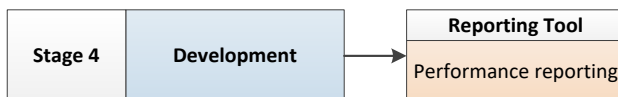
1. POD PF performance overview
2. POD daily and historic performance profiles

The first section provides a tabular overview of key performance indicators such as:

- Excess reactive energy [kVArh]
- Maximum excess demand [kVA]
- Maximum demand [kVA]
- NMD [kVA]
- Average PF [Ratio]

There are three tables presented in the report, namely a daily, 14-day, and 31-day performance table. Figure 39 showcases the daily operation POD PF performance table.

These performance values are based on standard and peak time of use (TOU) data. The daily operation POD PF performance table provides an overview of the performance of a POD based on the previous day's data. The performance of the PODs are ranked in descending order based on the excess reactive energy usage as presented in Figure 39 by the "Excess Reactive Energy [kVArh]" column. This was done in fulfilment of Objective II to identify PODs with poor PF performance that need to be prioritised for investigations and to promote continuous improvement.



Tables 1.1 to 1.3 only account for standard and peak time-of-use (TOU). A penalty is allocated to the monthly Eskom bill based on the accumulated excess reactive energy [kVAh] measured during standard and peak TOU. This is only applicable from 1 June to 31 August (winter months). A poor power factor also increases the maximum demand [kVA]. Unlike the excess reactive energy, the maximum demand measured during standard and peak periods is billed throughout the year. The tables are sorted in descending order based on the excess reactive energy.

Table 1.1: *Daily Operation POD Power Factor Performance*

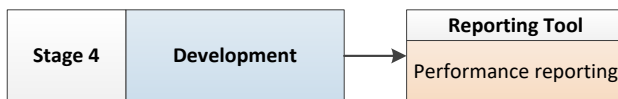
Operation	Excess Reactive Energy [kVAh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Avg. PF [-]
PODs	140 541	7 610	40 016	60 000	0.86
	81 229	5 783	52 965	77 500	0.92
	80 572	3 799	36 644	48 000	0.89
	74 870	2 879	22 014	27 000	0.87
	71 357	4 449	17 548	20 000	0.83
	68 108	6 340	50 664	40 000	0.93
	66 326	3 137	31 728	47 000	0.91
	44 201	1 530	9 831	13 500	0.84
	28 224	1 808	6 157	15 000	0.65
	23 134	1 106	7 824	23 000	0.88
	22 013	1 491	18 419	23 000	0.93
	13 189	822	4 441	8 350	0.74
	11 696	602	7 353	8 500	0.92
	9 217	1 066	11 744	12 500	0.91
	3 199	425	7 509	9 500	0.95
	2 595	231	3 383	5 500	0.94
	1 743	1 098	15 825	24 500	0.98
	1 735	73	309	8 000	0.78
	1 075	282	5 399	8 000	0.96
	409	283	6 249	11 000	0.97
	160	31	873	3 500	0.96
	146	1 062	25 716	31 000	0.98
	125	1 302	30 830	39 000	0.97
	21	305	7 485	11 000	0.98
	0	525	18 441	24 000	0.98
	0	6	1 488	2 700	1.00
	0	516	16 911	23 000	0.98
	0	192	9 294	15 300	0.99
	0	1 290	42 653	72 000	0.99
	0	259	30 060	31 000	1.00
	0	0	40	11 000	1.00
	0	780	36 702	53 000	0.99
	0	141	7 963	13 000	0.99

Figure 39: Power factor report – daily operation POD power factor performance table

The average power factor, indicated by the “Avg. PF” column, is colour coded with green, orange, and red which signify the following:

- Green indicates a PF above 0.96.
- Orange indicates a PF below 0.96 and equal to or above 0.90.
- Red indicates a PF below 0.90.

This, in combination with the PODs sorted based on the excess reactive energy usage, was done to enable swift identification of poor performing operations for further investigation.



The notified maximum demand represented as the “NMD” column in Figure 39 is used to identify whether the maximum demand [kVA] of a POD exceeded its agreed NMD. This is indicated by highlighting the maximum demand value of a POD in red when it has exceeded its NMD as seen in Figure 43.

Table 1.2: 14 Day Operation POD Power Factor Performance

Operation	Excess Reactive Energy [kVArh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Avg. PF [:]
PODs	1 535 915	9 258	46 330	60 000	0.86
	826 707	3 183	22 307	27 000	0.87
	819 168	5 823	61 549	77 500	0.93
	721 641	3 275	35 484	47 000	0.91
	633 582	4 050	44 196	48 000	0.92
	530 964	6 340	53 780	40 000	0.94
	467 164	4 449	17 548	20 000	0.89
	444 199	1 632	10 111	13 500	0.84
	274 395	1 345	9 062	23 000	0.85
	258 444	1 730	18 419	23 000	0.92
	196 300	1 926	8 017	15 000	0.84
	115 622	622	7 434	8 500	0.92
	103 891	1 200	4 992	8 350	0.82
	87 863	1 070	12 031	12 500	0.91
	87 545	2 967	18 159	24 500	0.96
	71 787	885	9 543	11 000	0.92
	67 571	3 859	27 562	31 000	0.97
	35 110	2 491	33 694	39 000	0.97
	26 303	455	8 091	9 500	0.95
	19 818	83	324	8 000	0.76
	19 263	6 599	12 311	11 000	0.96
	15 141	1 108	5 662	8 000	0.95
	14 949	236	4 100	5 500	0.95
	2 243	958	20 290	24 000	0.98
	1 427	36	950	3 500	0.96
	401	558	18 347	23 000	0.99
	0	19	1 500	2 700	1.00
	0	236	12 442	15 300	0.99
	0	1 387	45 339	72 000	0.99
	0	621	32 003	31 000	1.00
	0	12	4 726	11 000	1.00
	0	1 143	39 292	53 000	0.99
	0	176	8 470	13 000	0.99

Figure 40: Power factor report – 14-day operation POD power factor performance table

These tables aim to assist the user when comparing the performance of the various operations in terms of their PF performance and to swiftly identify poor performing operations that need attention.

The second section provides a daily and historic power performance graph for each operation POD. These graphs can be viewed as an extension of the performance tables, as they provide further detail regarding the performance values presented in Figure 39 and Figure 40. An example of the daily and historic POD power profiles is showcased in Figure 41.

2.32

POD

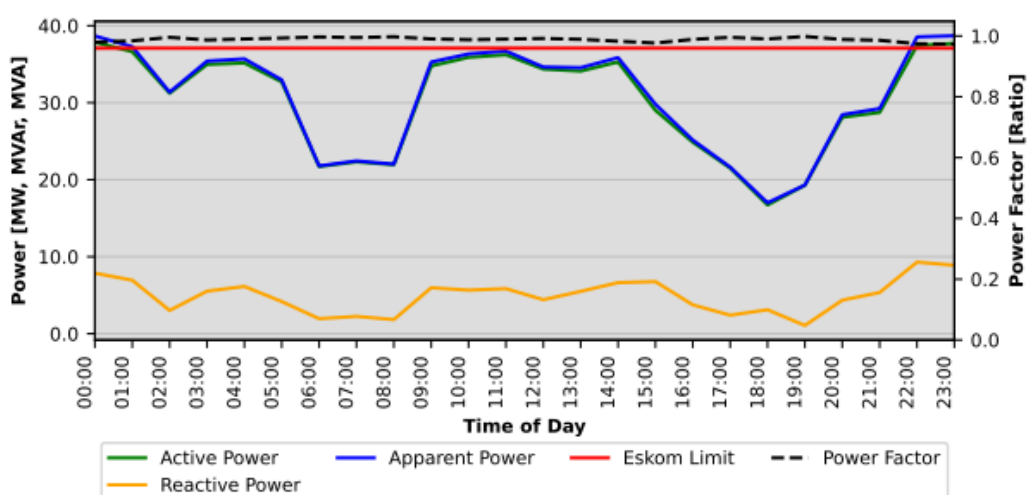


Figure 2.63: Daily **POD** Performance

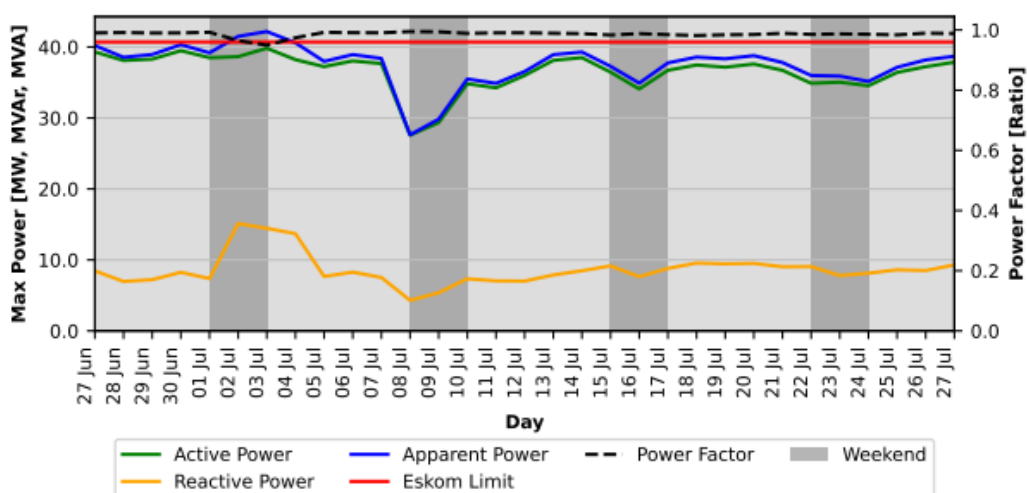
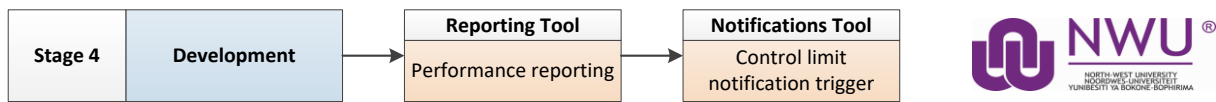


Figure 2.64: Historic **POD** Performance

Figure 41: Power factor report – daily and historic POD performance profiles



The daily POD power performance graph, as presented in Figure 41, provides an hourly overview of the previous day's power performance with regards to the following power data:

- Active power [MW] – represented by the green solid line data profile.
- Reactive power [MVar] – represented by the orange solid line data profile.
- Apparent power [MVA] – represented by the blue solid line data profile.
- POD PF [Ratio] – represented by the black dashed line data profile.
- Eskom Limit [Ratio] – represented by the red solid line data profile.

The Eskom limit denotes the PF value of 0.96 which is used to gauge whether excess reactive power is being consumed as discussed in Section 1.3.3 in the background of this study. The POD PF can, therefore, be compared to the Eskom limit to identify whether the performance meets Eskom's POD requirements and whether penalties will be avoided during standard and peak TOU.

The primary y-axis of the daily performance graph indicates the performance of the active, reactive, and apparent power consumption of the POD whilst the secondary y-axis shows the corresponding PF performance. The x-axis showcases the hourly time interval of the measured power data.

The historic performance graph showcases the maximum 24-hour power readings of the same power data presented in the daily performance graph over 31 days. Weekends are also indicated by the dark grey areas on the graph as seen in Figure 41. This helps distinguish weekdays from weekends and allows the user to gauge what day of the week the data represents. For example, 02 July is a Saturday (start of the weekend), and 03 July is a Sunday (end of the weekend); thus, 04 July and 08 July signify Monday and Friday respectively.

The daily report can be a useful tool to swiftly revise the PF performance of various PODs and assist in identifying potential issues. It can also be used to keep records of past performances to establish the impact certain system changes had on the PF performance of an operation POD.

Notification system

The PF notification system provides an additional layer of monitoring and identification of poor PF performance. It was created using PTB and is integrated with the MTB web and mobile application. Figure 42 showcases the notification system constructed in PTB.

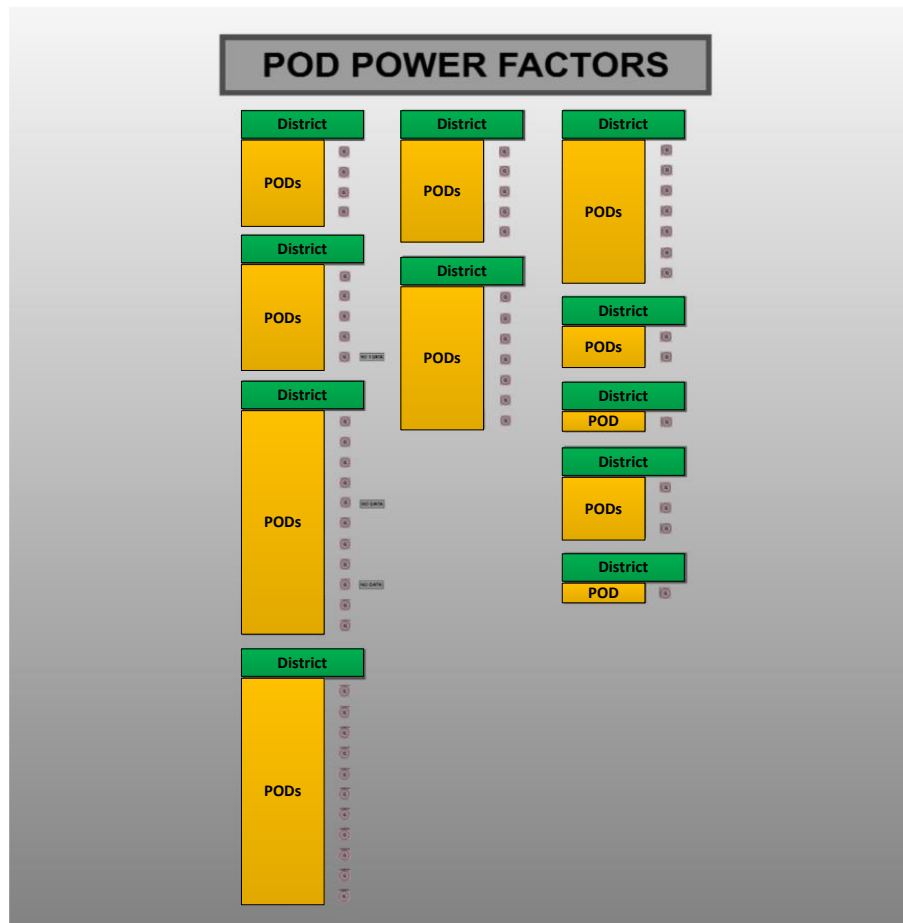


Figure 42: PTB Notification system

An instrumentation box is used to log each POD's active, reactive, and apparent power consumption and then used to calculate the PF of the POD based on the available power data. A closer view of the instrumentation box is presented in Figure 43.



Figure 43: PTB notification system – instrumentation box

The instrumentation box provides live feedback on the MTB web-application regarding the PF performance and data status, as illustrated in Figure 43. A red circle around the instrumentation box indicates that the set PF limit has been exceeded, whilst an orange circle



indicates data loss. If there is no circle around the instrumentation box it indicates that data is available, and the PF performance is within the set limit.

As described in Section 1.6.3, three-sigma control charts are considered one of the fundamental quality monitoring tools and are implemented in various industries. For this reason, a three-sigma control chart was selected to setup the PF limits of the PODs based on three standard deviations from the mean PF performance. The mean PF performance and sample standard deviation was calculated using Equation 9 and Equation 11. A sample size of 12 months was selected to set up the PF control limit for each deep-level mine operation POD.

The PF limit is not fixed and can be adjusted based on the performance of the POD to accommodate for system changes that are viewed as normal operation. This is also relevant when there are updates in the PFC equipment that affect the PF performance. In this case, updating the PF limit should be considered to improve the accuracy of the PF notifications.

Additional to the ability to adjust the PF limit, there are various settings available regarding the notification trigger. Figure 44 provides an overview of the available notification settings.

Notification [X]

Name POD **Status** Internal [v]

Parameters Groups Tags Calcs

Parameters [Default]

Frequency [1] [Hours] [v] How often this notification will be checked.

Dead-Time [1] [Hours] [v] The least time to pass before another notification is send.

Interval [1] [Hours] [v] The size of the data intervals being requested.

Range [4] [Hours] [v] Needed to calculate the from date based on to date. Indicated in days.

Start [] [] [] If set, start notification check then.

[Accept] [Cancel]

Figure 44: PTB Notification system – notification settings



The notification parameters, as shown in Figure 44, that can be adjusted are:

- Frequency – refers to the time interval between notification limit checks.
- Dead-time – refers to the time delay between notifications.
- Data interval – refers to the data intervals to be examined for limit infringement.
- Data range – refers to data sample size to be examined for limit infringement.
- Start time – refers to a set start time from which notification limit checks may commence.

These parameters will be adjusted based on feedback from mine personnel. The default POD PF limit notification settings are shown in Figure 44. Various contact lists can be created in PTB and linked to individual POD PF notification limits. The availability of this customisation assists in preventing users from being bombarded with notifications, as they will only be linked to relevant POD PF notifications.

The notifications are received by the user via the MTB mobile application on a cellular device. Figure 45 provides an example of the limit notification a user will receive based on the set PF limit and notification parameters.

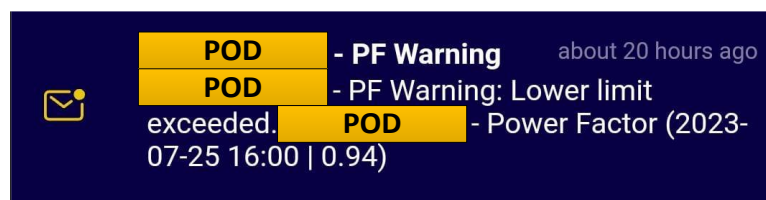


Figure 45: MTB mobile application power factor limit notification

The notification highlights the operation POD that received a PF warning notification due to its set limit being exceeded. The average PF value is presented which triggered the limit notification based on the set notification parameters. Furthermore, the date and time of the notification is also presented in the notification message.

The notification history log can be accessed in the MTB mobile application by selecting the “Notification” label in the application menu as shown in Figure 46.

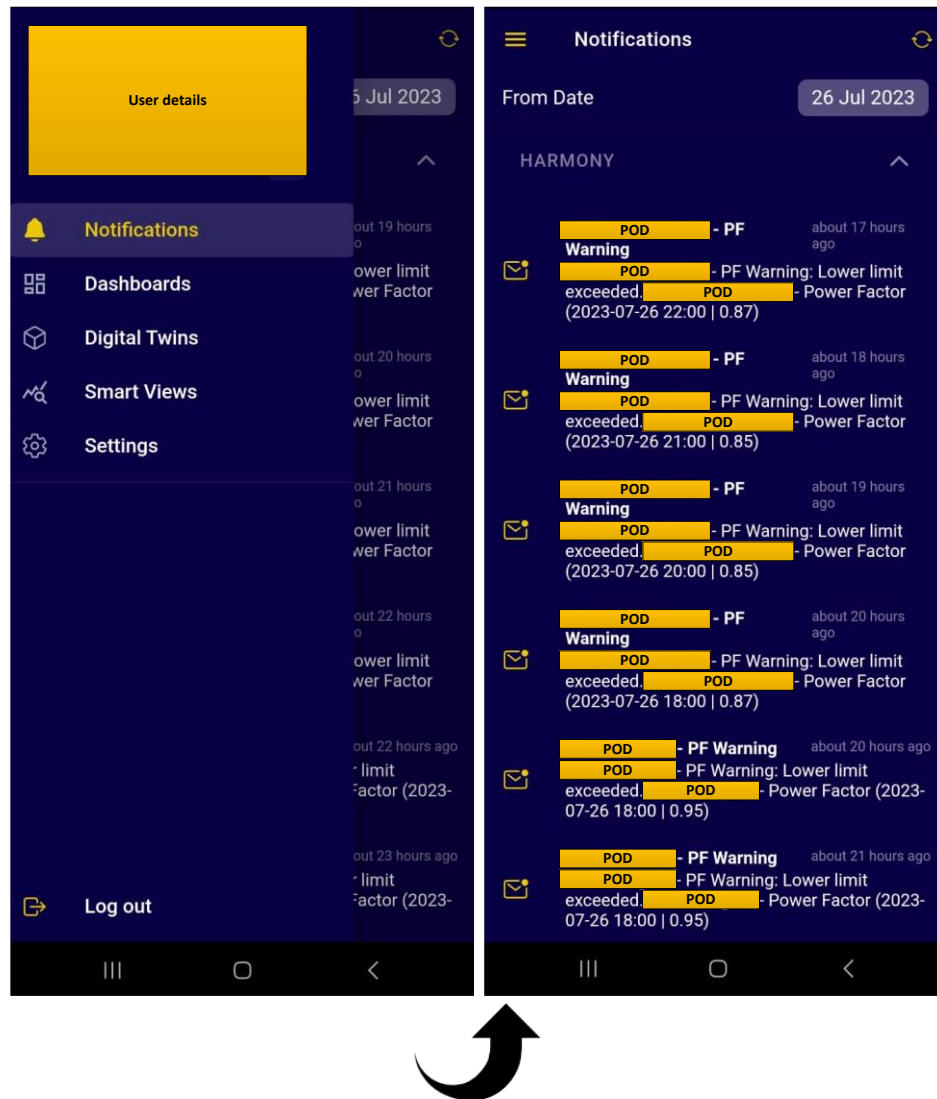


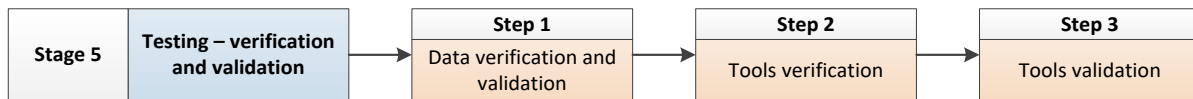
Figure 46: MTB mobile application notification history log

The date from which the notification history is to be viewed can be selected in the top right corner. The MTB mobile application is used as the primary resource of receiving PF notifications; however, the option to receive notifications via an SMS is also available.

The aim of the notification system is to allow relevant personnel to stay informed regarding changes in the POD PF performance, especially when they are not able to access a personal computer to monitor the performance via the monitoring and data visualisation tool.

This concludes the overview of the developed PFM tools. The following stage in the SDLC is the testing stage where the tools were verified and validated.

3.2.6 Stage 5: Testing



After the development stage, the data sources and tools were subjected to verification and validation to identify and rectify potential errors in the systems before being deployed for use. The requirements outlined in Section 3.2.3 were satisfied.

3.2.6.1 Data verification and validation

As discussed in Section 2.6, the data sources (iST ecWin and SCADA) were deemed credible due to these sources already being utilised by the case study mine group for daily energy management decision-making and performance monitoring; thus, verifying the data for use. The validity of the data was determined by calculating and comparing the following performance metrics with the figures presented in the monthly Eskom electricity bill:

- Total active energy consumption [kWh]
- Maximum demand [kVA]
- Total excess reactive energy [kVArh]

The performance metrics were calculated using Equation 1, Equation 16, and Equation 18 as outlined in Table 15. The applicable TOU periods were considered. The MAPE value was determined for the above performance metrics across the Eskom electricity bills (June 2021 to September 2021). The resulting MAPE values for each case study POD are presented in Table 26.

Table 26: Data validation - data source versus Eskom MAPE

Data Validation			
POD	Performance Metrics Disparity (Data Source versus Eskom Figures)		
	kWh MAPE [%]	kVA MAPE [%]	kVArh MAPE [%]
H1	7.8	8.9	9.0
F1	3.3	0.5	2.7
G1	0.4	0.9	8.3
C1	0.6	1.4	4.6
B2	1.0	6.7	7.9
A2	1.0	0.9	11.8
B1	0.7	3.0	103.8
I1	0.7	1.4	492.3
E1	0.9	2.4	107.0
A1	2.1	2.4	Undefined (divide by 0)
D1	0.2	0.2	Undefined (divide by 0)



The MAPE values for the total active energy consumption [kWh] and maximum demand [kVA] performance metrics were all below 10%, indicating a high accuracy. The disparity between the data source values and the Eskom figures was anticipated and can be attributed to variances in the instrumentation used and the calibration thereof between Eskom and the various mine operations.

The calculated excess reactive energy over the four-month period was less accurate than the calculated kWh and kVA when comparing the MAPE values. In general, the calculated kVARh exceeded the kVARh value indicated on the Eskom electricity bill. As discussed in Section 1.3.3, the penalties allocated when exceeding the NMD have a deadband of 5%. Although not explicitly stated on the Eskom tariff booklet, there might also be a similar deadband applied to the recorded excess reactive energy.

A regression trend in terms of the total excess reactive energy consumption [kVARh] was also identified with the MAPE values presented in Table 26. As the total excess reactive energy consumption of the PODs decreased (seen in Table 17), a general increase in the MAPE value over the four-month period was observed in Table 26.

This observation in the MAPE values from PODs B1 to D1 is due to the underlying issue of how the MAPE value is influenced by values of a low range. For example, an expected value of 3 and a true value of 2 indicate an error of 50%, but the difference between the two values is only 1. Meanwhile, if the expected value was 101 and the true value was 100, the error would be 1% where the difference between the two values is also 1⁷⁰.

The undefined MAPE values for PODs A1 and D1 are due to months where no excess reactive energy was recorded (average PF between 0.96 and 1) and results in an undefined value when the error is calculated (division by zero). Therefore, the relatively low excess reactive energy consumption of PODs B1 to D1, especially when compared to PODs H1 to A1 in Table 17, can be attributed to the occurrence of these high and undefined MAPE values.

Taking this into account, along with the majority of the MAPE values being below 10%, the data sources are deemed valid for their intended use.

⁷⁰ A. M. Sefidian, 'A guide on regression error metrics (MSE, RMSE, MAE, MAPE, sMAPE, MPE) with Python code', 2023. <http://sefidian.com/2022/08/18/a-guide-on-regression-error-metrics-with-python-code/> (accessed Aug. 10, 2023).



3.2.6.2 Verification of power factor management tools

As discussed in Section 2.6.1, the purpose of the verification process is to establish whether the PFM tools are correct and truthful with regards to their specifications and output. The tools were verified by replicating the calculations of the tools in Excel and comparing these expected results with the output of the tools. The MAPE was calculated to establish the accuracy of the tools when compared to the expected output. Visual illustrations were also used to compare the expected output and the actual output for large datasets where applicable alongside the MAPE.

POD C1 was randomly selected to showcase the verification of the PFM tools.

Web-based monitoring and data visualisation tool

The monitoring and data visualisation tool was verified by comparing the tool output from the data analysis page, as seen in Figure 33, to that of the calculations in Excel. A period selection of the last 32 days was selected for verification. POD C1 has four incomers as shown in Figure 33. The resulting data presented in the graph was extracted through the data extraction option as shown in Figure 35 and Figure 36.

Table 27 showcases the value comparison between the output of the tool versus the expected output as calculated in Excel for POD C1 Incomer 1.

Table 27: Web-based monitoring and data visualisation tool output verification

Output Verification			
Date & Time	POD C1 Incomer 1 Power Factor [Ratio]		Error [%]
	Tool Output	Excel Output	
07/08 00:00	1.00	1.00	0
07/08 00:30	1.00	1.00	0
07/08 01:00	1.00	1.00	0
07/08 01:30	1.00	1.00	0
07/08 02:00	1.00	1.00	0
07/08 02:30	1.00	1.00	0
07/08 03:00	1.00	1.00	0
.	.	.	.
.	.	.	.
.	.	.	.
08/08 06:00	0.91	0.91	0
08/08 06:30	0.91	0.91	0
08/08 07:00	0.99	0.99	0
08/08 07:30	0.99	0.99	0



The error percentage between the tool output and the Excel output (expected output) is zero percent for all the data points. The resulting MAPE value was 0%, which was anticipated due to the tool and Excel using the same data source and, therefore, the same output is expected.

Figure 47 and Figure 48 provide an overview of the visual comparison between the output from the tool and that of Excel with the same input data.

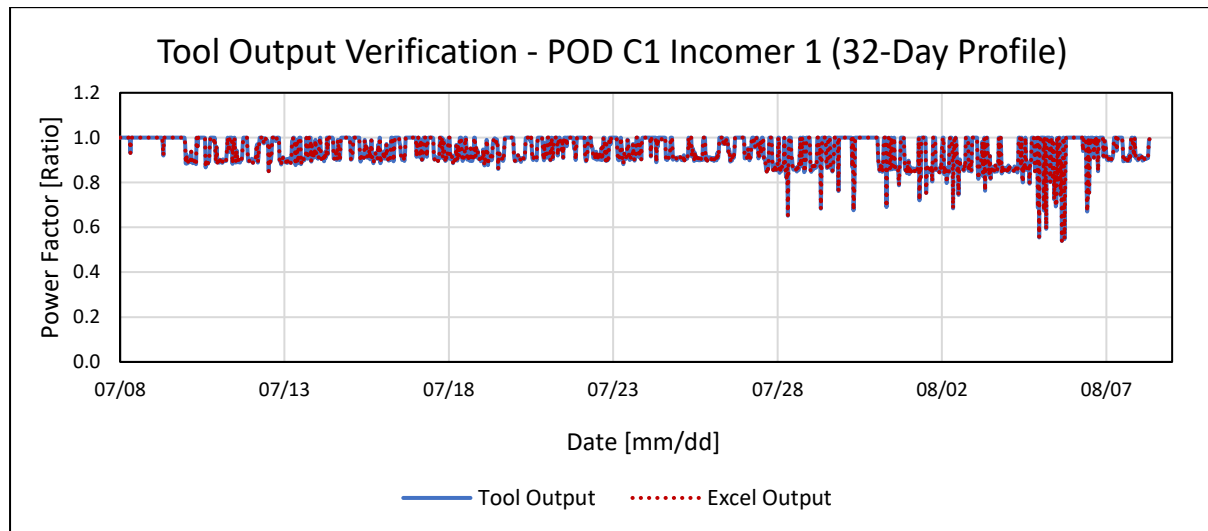


Figure 47: Web-based monitoring and data visualisation tool output verification – 32-day profile

Figure 47 illustrates how the output from the monitoring and data visualisation tool match the output of Excel over the 32-day data period selection. Figure 48 provides a closer look by narrowing down the data period to 1 day (07/18 to 07/19) in Figure 47.

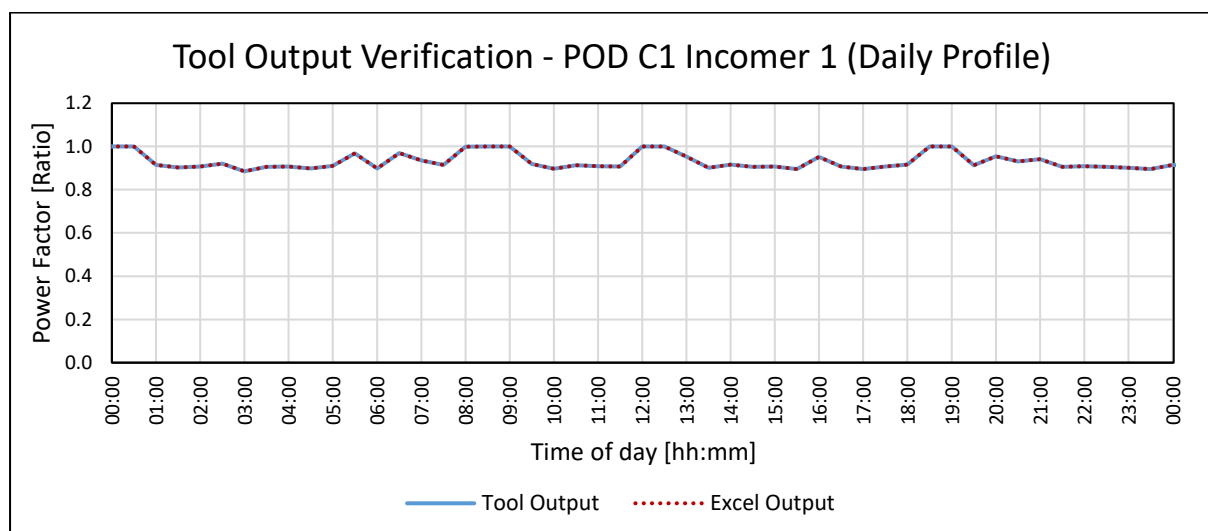


Figure 48: Web-based monitoring and data visualisation tool output verification – daily profile

Table 27 along with Figure 47 and Figure 48 illustrates how the output of the web-based monitoring and data visualisation corresponds with the expected output from Excel. The



resulting MAPE value of 0 confirms the accuracy of the tool presented in the visual illustrations. The verification of Incomers 2, 3, and 4 of POD C1 is presented in Appendix I.

Daily and historic power factor performance report

The daily and historic PF performance report was verified by comparing the values presented in the report with the values calculated in Excel. As discussed in Section 3.2.4, the report is split into two main sections:

1. POD PF performance overview (tabular summary)
2. POD daily and historic performance profiles (profile summary)

The values presented in the daily, 14-day, and 31-day performance tables in the first section were verified by comparing the expected output calculated in Excel for POD C1.

The performance metrics were calculated using Equation 1, Equation 16, and Equation 18. These equations are also outlined in Table 15. As discussed in Section 3.2.4, the performance tables are based on standard and peak TOU data. This was, therefore, considered with the setup of the Excel calculations. The daily performance values generated by the report over the selected period are presented in Figure 49.

Operation	Excess Reactive Energy [kVAh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Avg. PF [:]
POD C1	0	586	35 787	53 000	0.99

Figure 49: Power factor report – daily performance table values for POD C1

The comparison between the output of the report and the output from Excel for the daily performance table is presented in Table 28.

Table 28: Power factor report – daily performance table output verification

Daily Performance Table Output Verification						
POD	Output	Excess Reactive Energy [kVAh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Average PF [Ratio]
C1	Report	0	586	35 787	53 000	0.99
	Excel	0	586	35 787	53 000	0.99
Error		-	0%	0%	N/A	0%

The 14-day performance values generated by the report over the selected period are presented in Figure 50.



Operation	Excess Reactive Energy [kVArh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Avg. PF [:]
POD C1	0	1 143	39 292	53 000	0.99

Figure 50: Power factor report – 14-day performance table values for POD C1

The comparison between the output of the report and the output from Excel for the 14-day performance table is presented in Table 29.

Table 29: Power factor report – 14-day performance table output verification

14 Day Performance Table Output Verification						
POD	Output	Excess Reactive Energy [kVArh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Average PF [Ratio]
C1	Report	0	1 143	39 292	53 000	0.99
	Excel	0	1 143	39 292	53 000	0.99
Error		-	0%	0%	N/A	0%

The 31-day performance values generated by the report over the selected period are presented in Figure 51.

Operation	Excess Reactive Energy [kVArh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Avg. PF [:]
POD C1	17 171	2 427	39 292	53 000	0.99

Figure 51: Power factor report – 31-day performance table values for POD C1

The comparison between the output of the report and the output from Excel for the 31-day performance table is presented in Table 30.

Table 30: Power factor report – 31-day performance table output verification

31 Day Performance Table Output Verification						
POD	Output	Excess Reactive Energy [kVArh]	Max Excess Demand [kVA]	Max Demand [kVA]	NMD [kVA]	Average PF [Ratio]
C1	Report	17 171	2427	39 292	53 000	0.99
	Excel	17 171	2427	39 292	53 000	0.99
Error		0%	0%	0%	N/A	0%

The error percentages presented in Table 28, Table 29, and Table 30 indicate that the output of the performance tables match the output generated in Excel. The NMD value is a manual input that is obtained from the Eskom electricity bill and, therefore, a percentage error is not applicable.

The second section of the report, POD daily and historic performance profiles, was visually verified through a profile comparison due to the output data of the report not being available for extraction.

The performance profiles presented in this section of the report are split into a daily (24-hour period) and a 31-day period performance profile. These profiles provide an overview of the active, reactive- apparent power and PF performance of a POD. The daily performance profile generated by the reporting tool is presented in Figure 52. These profiles showcase the hourly power performance data over a 24-hour period for the previous day.

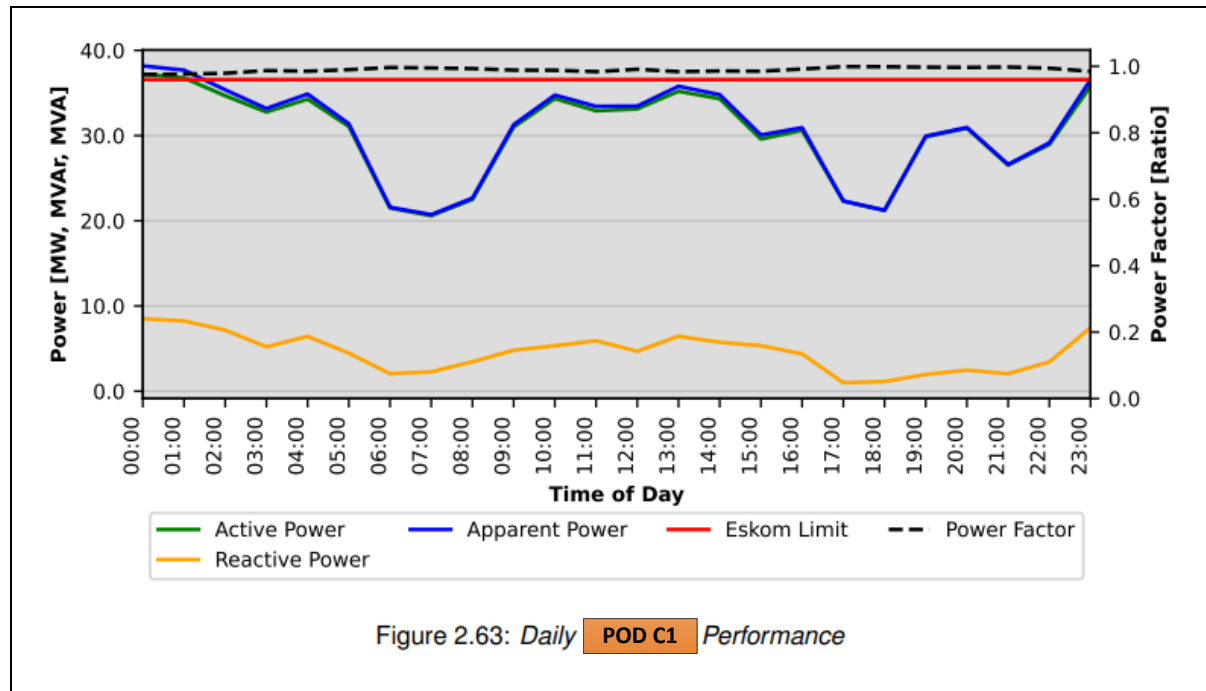
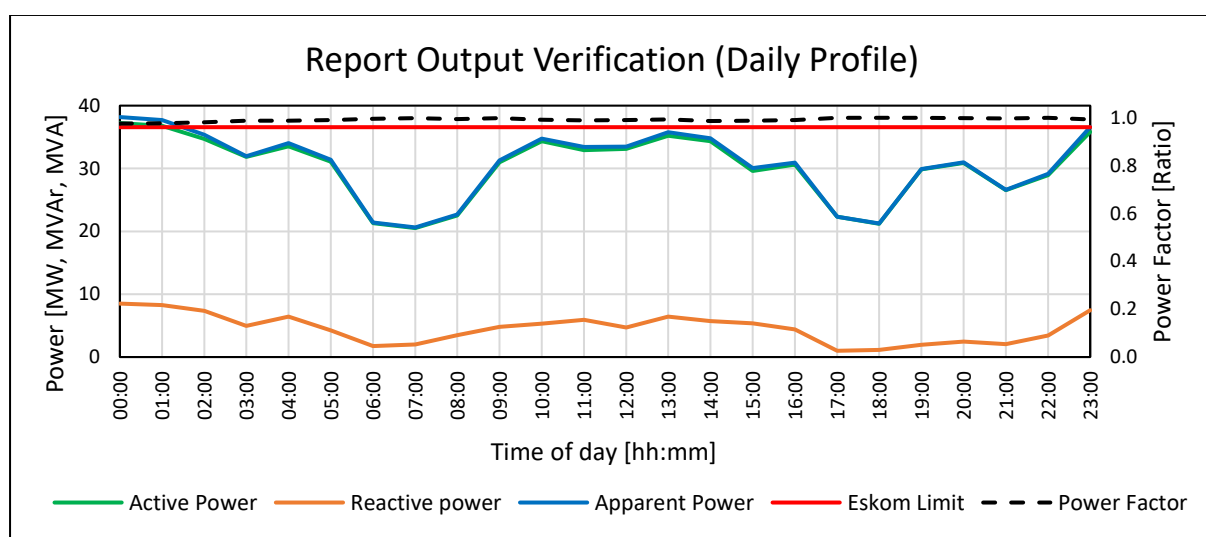


Figure 52: Power factor report – POD C1 daily performance profile

The corresponding graphical output generated by Excel for Figure 52 is presented in Figure 53.





The historic performance profile generated by the reporting tool is presented in Figure 54. These profiles showcase the daily maximum power performance data for the previous 31 days.

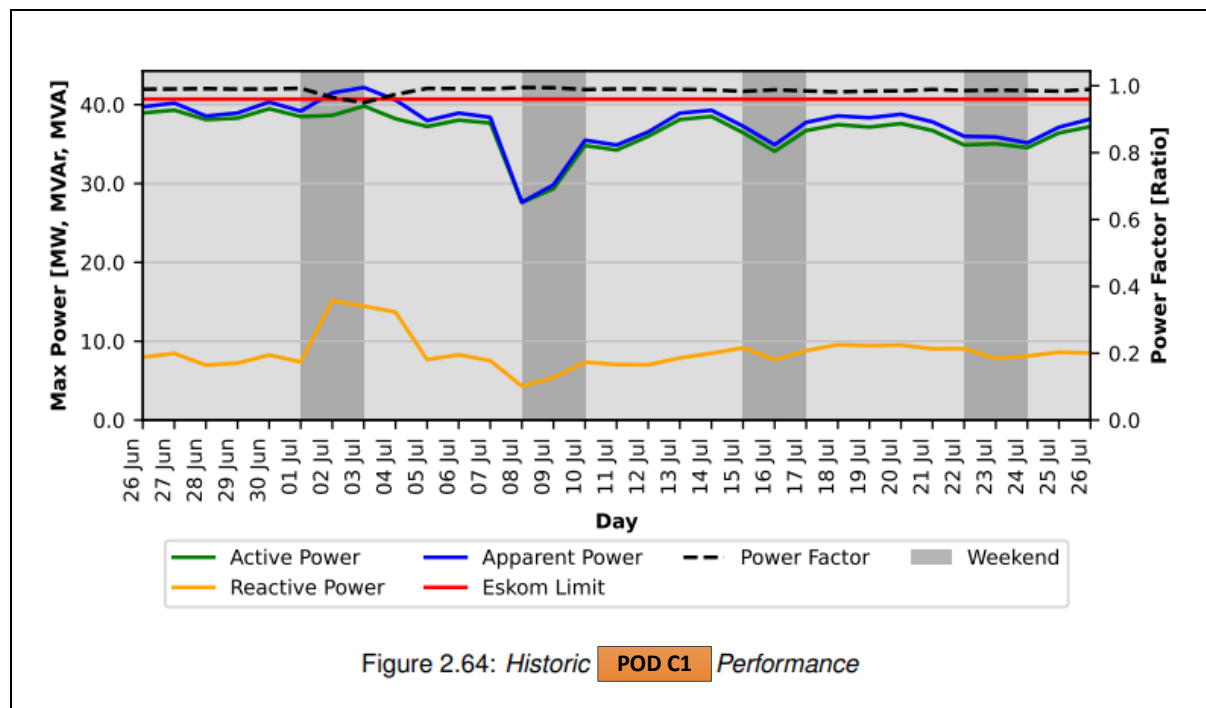


Figure 54: Power factor report – POD C1 historic performance profile

The corresponding graphical output generated by Excel for Figure 54 is presented in Figure 55.

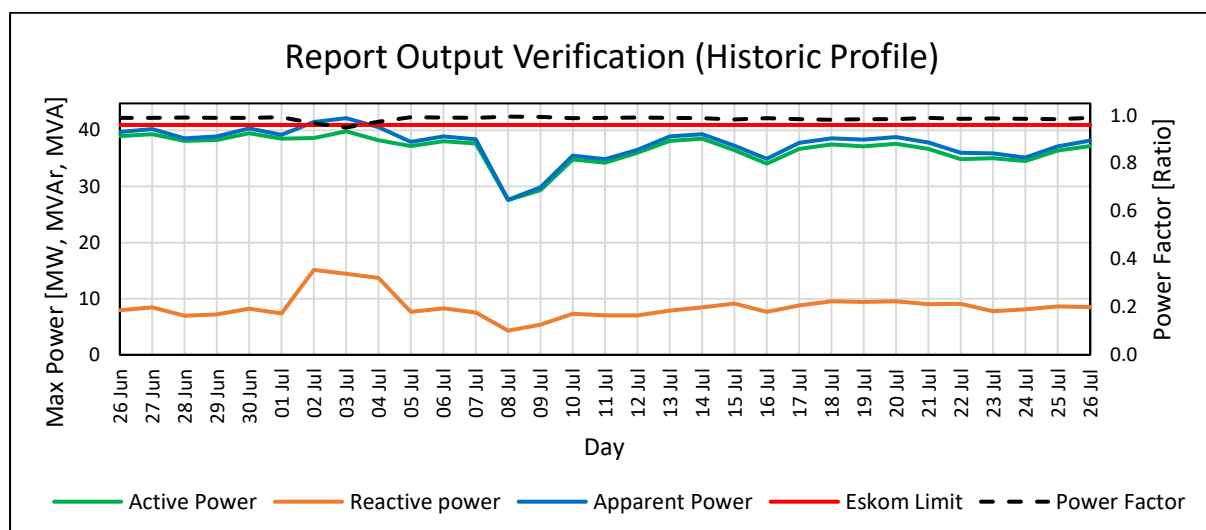


Figure 55: Power factor report – historic performance profile output verification

The visual comparisons between Figure 52 and Figure 53 and Figure 54 and Figure 55, for the performance profile section of the report, showcases the output accuracy of the report.



The visual presentation of the performance profile figures correspond with the output accuracy indicated by the verification of the performance tables as presented in Table 28, Table 29, and Table 30.

Notification system

The notification system was verified by establishing whether the notification triggered satisfied the notification settings by investigating the source data in Excel. The PF reporting, monitoring, and data visualisation tools will be examined to determine whether the output of these tools correspond with the notification.

The PF limit of POD C1 is set to 0.97. As discussed in Section 3.2.5, the limits were calculated based on three standard deviations from the mean PF performance over a 12-month period. In addition, the range of the notification system is set to four hours as presented in Figure 44. This indicates that the previous four hours are examined to establish whether the average PF performance over the period is below the set limit of 0.97. Therefore, if the average PF recorded in the last four hours is below 0.97, a notification will be sent out to the relevant recipients.

Figure 56 and Figure 57 showcase notifications that were received through the MTB mobile application for POD C1.

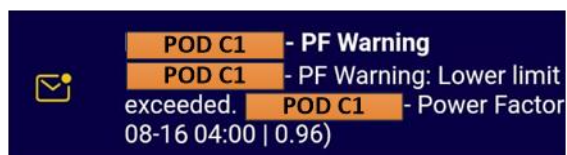


Figure 56: Power factor notification output #1

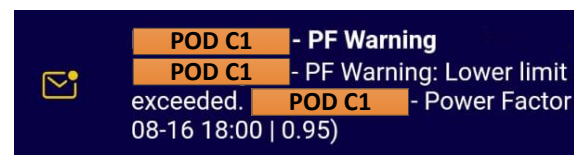


Figure 57: Power factor notification output #2

Figure 56 indicates that the average PF of POD C1 was below 0.7 between 00:00 and 04:00, with an average PF of 0.96. Similarly, Figure 57 indicates that the PF on the same day was below 0.97 between 14:00 and 18:00, with an average PF of 0.95 during this period.

Figure 58 showcases the PF data recorded for POD C1 on the day the two notifications were distributed.

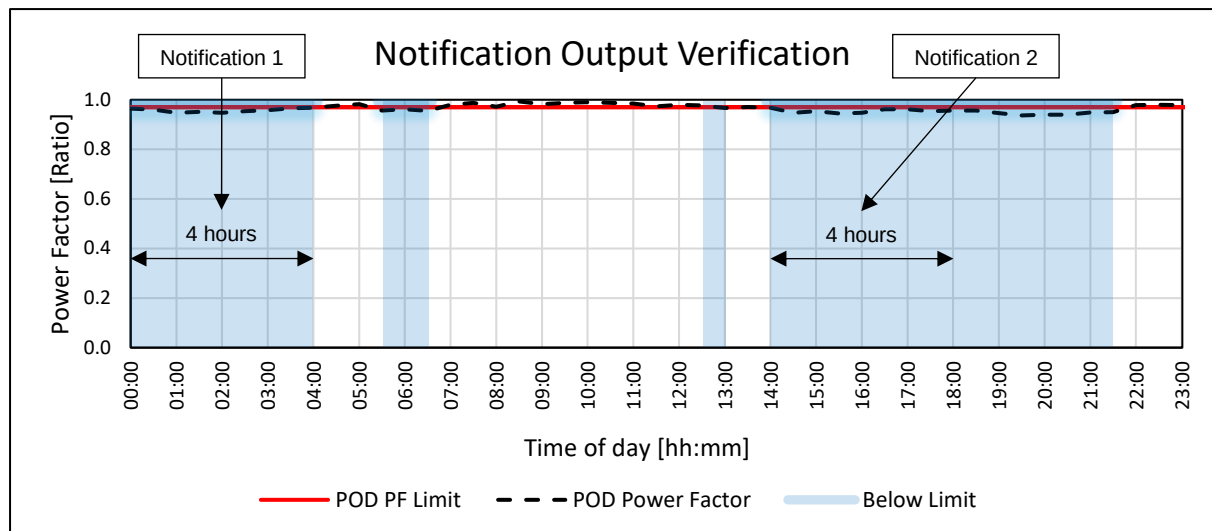


Figure 58: Power factor notification system – data verification profiles of POD C1

The light blue area on the graph seen in Figure 58 highlights the periods where the recorded PF values were below the POD limit of 0.97. The raw data illustrated in Figure 58 is presented in Figure 59.

Notification Verification	
Date & Time	Power Factor
08/16 00:00	0.964
08/16 00:30	0.960
08/16 01:00	0.948
08/16 01:30	0.951
08/16 02:00	0.947
08/16 02:30	0.954
08/16 03:00	0.957
08/16 03:30	0.966
08/16 04:00	0.969
.	.
.	.
.	.
08/16 14:00	0.968
08/16 14:30	0.947
08/16 15:00	0.954
08/16 15:30	0.945
08/16 16:00	0.948
08/16 16:30	0.962
08/16 17:00	0.961
08/16 17:30	0.954
08/16 18:00	0.956

Average

0.96

Average

0.95

Notification

Figure 59: Power factor notification system – raw data verification of POD C1

Figure 59 highlights that the average PF between 00:00 and 04:00 is 0.96 and the average PF between 14:00 and 18:00 is 0.95. This matches the notifications received through the MTB mobile application as shown in Figure 56 and Figure 57. Furthermore, the PF daily performance report confirms the decline in PF performance of POD C1 when examining Figure 60 and Figure 61.

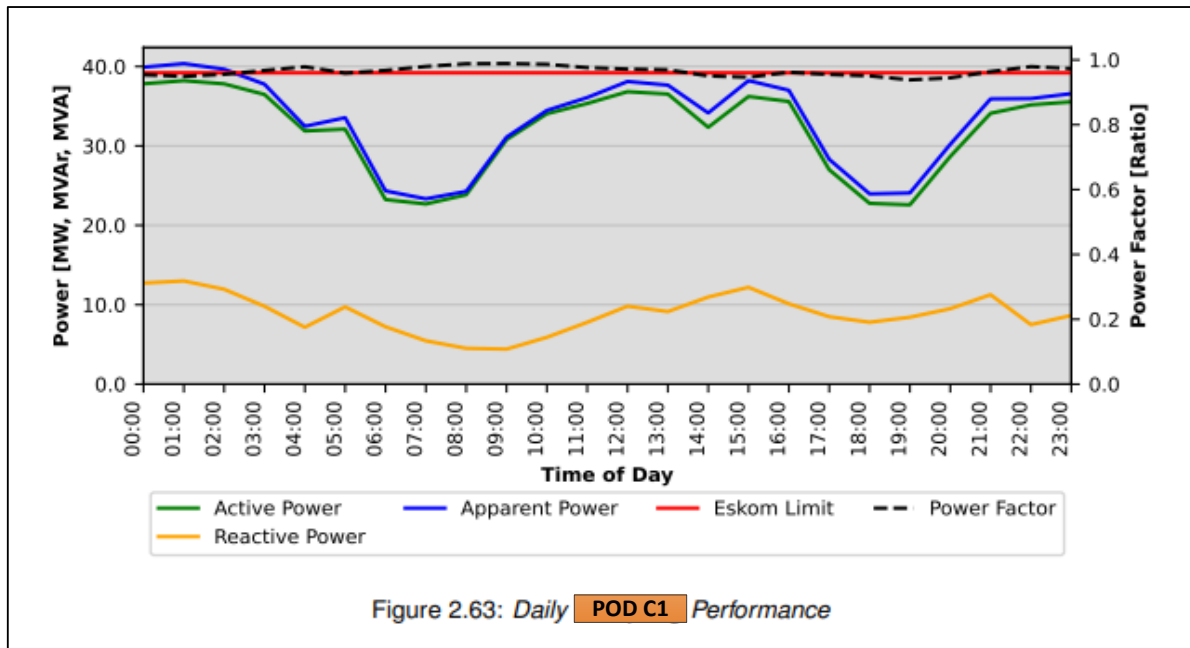


Figure 60: Power factor notification system – output verification via the daily performance profile

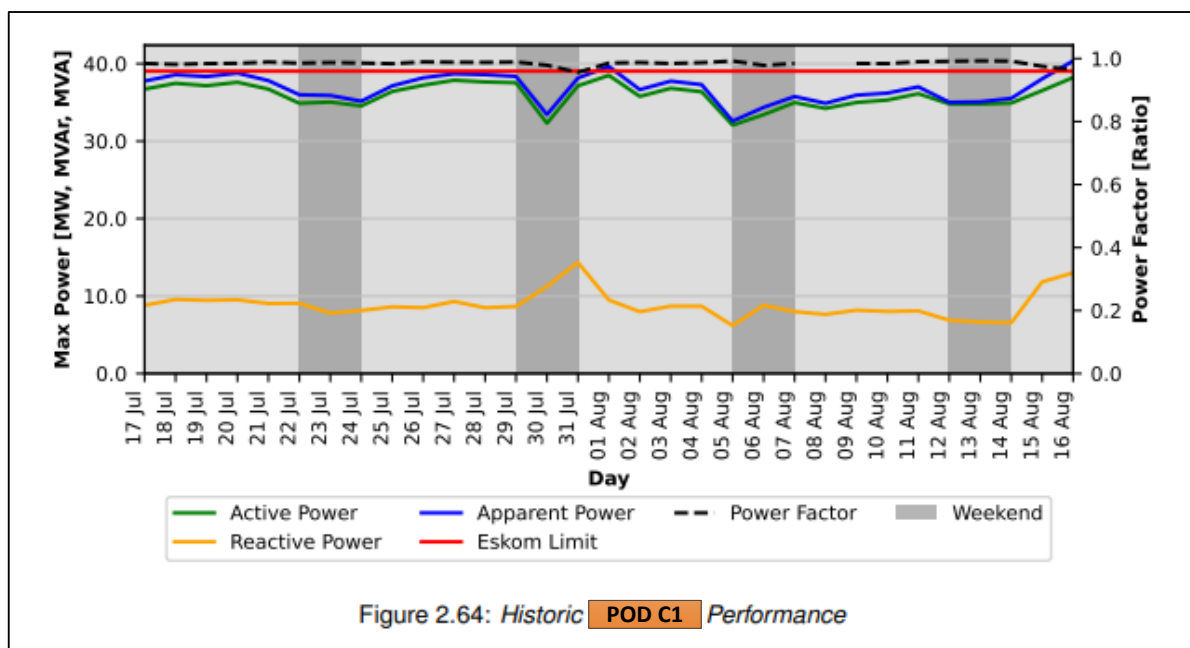


Figure 61: Power factor notification system – output verification via the historic performance profile



The decline in PF performance is less evident in the daily performance profile shown in Figure 60 than the historic performance profile displayed in Figure 61. However, when examining the daily performance profiles, the decline in the PF performance can be seen during the morning and late afternoon as the PF drops below the Eskom POD limit. During these periods, the difference between the active power and apparent power consumption increases, once again indicating a decline in the PF performance.

The decline in PF performance can be observed in the historic performance profile with a visible increase in the maximum reactive power consumption on the 15th and 16th of August. This corresponds with the increase in variation between the maximum active and apparent power consumption from the 15th of August.

The notifications along with the performance profiles suggest a potential issue with the PFC at POD C1. The PF monitoring and data visualisation tool should be used for further insight regarding the PF performance of POD C1. The analysis page of POD C1, from the monitoring and data visualisation tool, is shown in Figure 62.

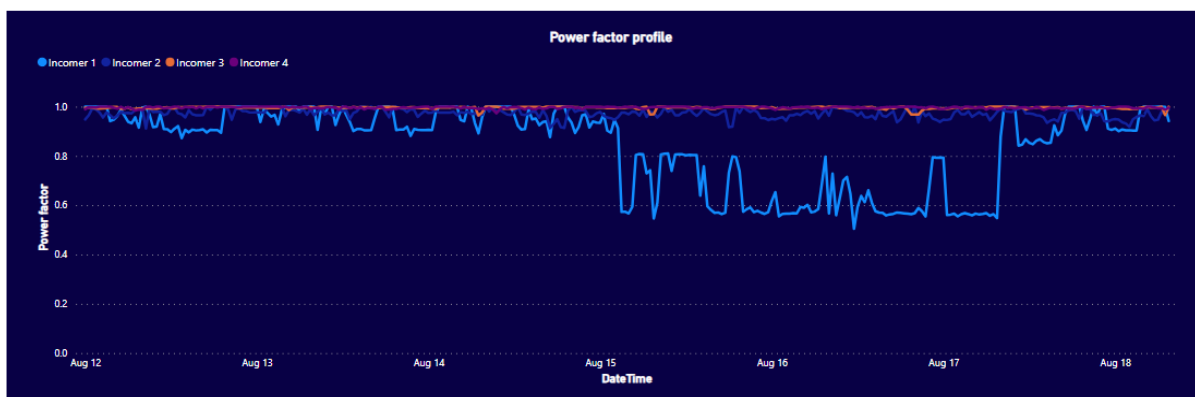


Figure 62: Power factor notification system – output verification via the data visualisation tool

A drop in the PF performance at Incomer 1 is visible from the 15th of August in Figure 62. The PF declines from approximately 0.90 to 0.60, confirming an issue with PFC at POD C1 with the root cause coming from Incomer 1. Subsequently, relevant site personnel were informed and the PFC of Incomer 1 was restored on the 17th of August as seen in Figure 62.

The verification of the notification system demonstrated how the tools can be effectively co-operated to proactively identify and address potential PFC issues. The PFM tools are deemed verified based on the analysis and visual examination of the output in Section 3.2.6.2. After the verification was concluded, the validation of the PFM tools commenced.



3.2.6.3 Validation of power factor management tools

As discussed in Section 2.6.2, the aim of the validation process is to establish whether the PFM tools satisfy the intended purpose of improving the PFM on deep-level mines. This was done in fulfilment of Objectives V and VI.

In fulfilment of Objectives III and IV, the PFM tools were validated by implementing the tools on the 11 PODs from the case study mine group as outlined in Section 3.2.2 (Table 14). The implementation of the tools was examined over the same period in 2022 as the performance analysis in Section 3.2.2. Therefore, the implementation of the tools took place between the June and September Eskom billing periods as outlined in Section 3.2.2 (Table 16).

The performance metrics as presented in Section 3.2.2 (Table 15) were used to measure the impact of the PFM tools pre- and post-implementation. Pre-implementation represents the 2021 June to September Eskom billing period and post-implementation represents the 2022 June to September billing period. The performance pre-implementation was established during the performance analysis stage in Section 3.2.2 and the results are summarised in Table 17 and Table 18.

A generic approach was employed during the implementation of the tools. The daily routine was to monitor the latest PF performance throughout the day using the PF monitoring and data visualisation tool. The daily and historic POD performances were revised once a day after the PF daily report was generated and distributed via email. If a PF limit notification was received via the MTB mobile application, the incomers of the specific POD were investigated utilising the PF monitoring and data visualisation tool to identify the incomers that were responsible for the reduced PF performance.

Based on the findings, relevant mine personnel were then contacted to inspect the status of the capacitor banks. Once the issue was identified, regular check-ins regarding the status of the capacitor banks were conducted until the problem was resolved.

The post-implementation results are presented in Table 31 and Table 32. The order of the PODs in Table 31 and Table 32 remained the same as the order presented in Table 17 and Table 18 of the performance analysis. As discussed in Section 3.2.2, Table 17 and Table 18 were organised in descending order based on the reactive energy consumption and reactive energy charges, respectively, to allow for swift evaluation of each POD's pre- and post-implementation PF performance.



Table 31: Case study post-implementation impact on reactive energy and apparent power consumption

Power Factor Performance Impact on kVArh and kVA (June – September 2022)						
Operation	POD	Average Power Factor	Excess Reactive Energy Consumption [kVArh]	Max Apparent Power Consumption [kVA]	Excess Apparent Power Consumption at Max Demand [kVA]	Estimated Capacitor Bank Downtime [h]
H	H1	0.87	2 130 112	17 804	6 883	1 529
F	F1	0.94	2 517 425	34 475	4 247	3 359
G	G1	0.97	80 159	18 162	3 376	254
C	C1	0.98	43 265	45 065	2 453	174
B	B2	0.97	95 988	7 587	160	131
A	A2	0.94	287 045	8 559	508	0
B	B1	0.96	63 457	9 887	565	0
I	I1	0.99	7 394	8 241	1 732	0
E	E1	0.98	45 995	21 063	730	0
A	A1	0.99	11 919	24 358	155	0
D	D1	0.99	0	19 352	3	0

The performance values shown in Table 31 were compiled and estimated in the same manner as the values presented in Table 17 of the performance analysis stage. As discussed in Section 3.2.2, the excess reactive energy consumption and capacitor bank downtime values are the totals for each POD over the implementation period. The maximum apparent power consumption represents the maximum kVA value recorded. The excess reactive energy and the maximum apparent power consumption values were gathered from the Eskom electricity bills.

The excess apparent power consumption was estimated at the maximum apparent power consumption reading of the POD across the implementation period. The electricity costs displayed in Table 32 were calculated based on the Eskom 2022/2023 tariffs, excluding VAT, as presented in Appendix C (Figure 80). The reactive energy charges were calculated at 21.03c/kWh while the total network demand charges and total excess network demand charges were calculated at R45.24/kVA/month.



Table 32: Case study post-implementation financial impact on reactive energy and demand charges

Power Factor Performance Impact on Electricity Costs (June – September 2022)						
Operation	POD	Average Power Factor	Total Reactive Energy Charge [R]	Total Network Demand Charge [R]	Total Excess Network Demand Charge [R]	Estimated Capacitor Bank Downtime [h]
H	H1	0.87	447 963	2 851 184	986 460	1 529
F	F1	0.94	529 414	6 003 164	617 164	3 359
G	G1	0.97	16 857	3 060 453	177 502	254
C	C1	0.98	9 099	7 825 919	336 676	174
B	B2	0.97	20 186	1 278 372	33 773	131
A	A2	0.94	60 366	1 503 745	81 765	0
B	B1	0.96	13 345	1 752 389	96 167	0
I	I1	0.99	1 555	1 273 801	79 506	0
E	E1	0.98	9 673	3 729 893	125 715	0
A	A1	0.99	2 507	4 070 086	29 632	0
D	D1	0.99	-	3 380 188	11 853	0

The total reactive energy charges and total network demand charges were obtained from the Eskom electricity bills, whereas the total excess network demand charges were calculated based on the estimated excess apparent power at the maximum apparent power consumption recorded during each respective month from June to September.

Figure 63 to Figure 67 illustrate the comparison between the performance metrics outlined in Table 17 and Table 31. These figures provide an overview of the pre- and post-implementation impact of the PFM tools on the PF performance of the various PODs.

Figure 63 compares the pre- and post-implementation impact of the PFM tools with regards to the average PF and excess reactive energy consumption of the various PODs. As discussed in Section 1.3.3, excess reactive energy is recorded at a PF of 0.96 and less; therefore, the PF limit presented in Figures 66, 69, and 70 is set to 0.96.

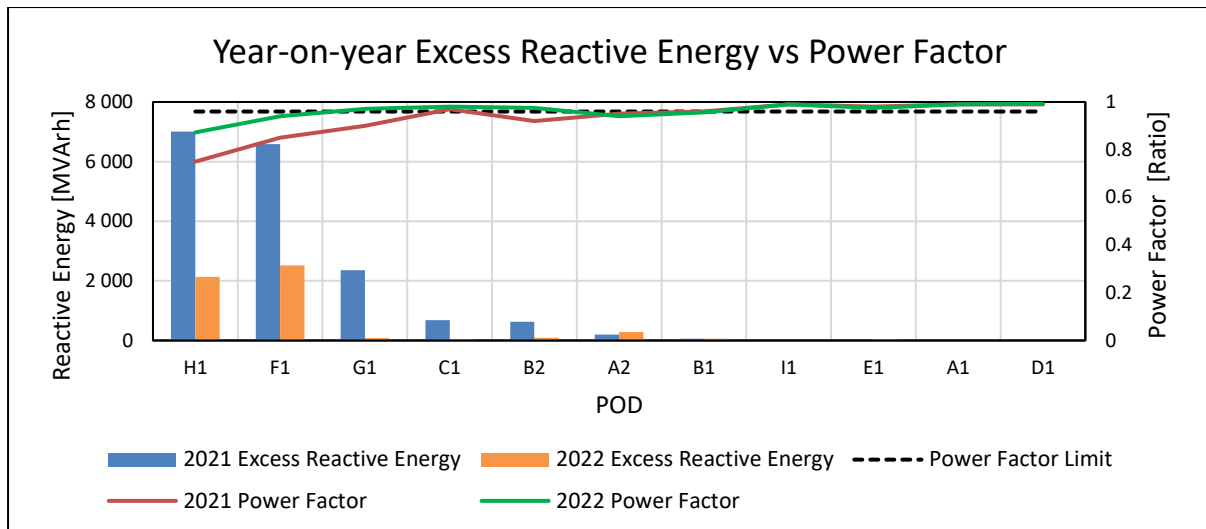


Figure 63: Case study post-implementation power factor impact on excess reactive energy

A general improvement of the average PF reading at the various PODs was realised when examining the pre-implementation (2021) and post-implementation (2022) performance in Figure 63, primarily for PODs H1, F1, G1, C1, and B2. Furthermore, the average PF of PODs G1 and B2 improved to 0.97, which is above the PF limit of 0.96.

This improved PF performance is reflected in the excess reactive energy consumption during 2022. The excess reactive energy recorded between June and September of 2022 was considerably less for these PODs when compared to 2021 (pre-implementation).

The only POD which saw a noticeable decrease in the average PF performance was POD A2, where the PF decreased from 0.95 to 0.94, which equates to a 1% reduction. This resulted in an 86 MVarh year-on-year increase in the excess reactive energy consumption for POD A2.

Although the average PF performance of PODs A2, B1, E1, and A1 were similar pre- and post-implementation, an increase in the year-on-year excess reactive energy consumption was realised across these PODs. An increase in the average active power (kW) baseload can be considered a contributing factor to these increases. Table 33 outlines the year-on-year increase in the average active power consumption of the case study PODs.



Table 33: Case study year-on-year average active power consumption

Year-on-year Active Power Consumption				
Operation	POD	Average Active Power Consumption [kW]		
		2021	2022	Increase
H	H1	12 352	13 855	1 504
F	F1	23 570	24 496	926
G	G1	11 706	12 714	1 007
C	C1	33 840	31 908	-1 932
B	B2	4 080	4 191	111
A	A2	5 458	5 463	5
B	B1	6 621	6 945	324
I	I1	2 242	2 267	25
E	E1	16 763	16 795	32
A	A1	21 902	23 355	1 453
D	D1	13 849	14 971	1 122

As discussed in Section 1.4.1, Equation 1, and Equation 3, if the active power consumption increases but the PF remains the same, the apparent power consumption and reactive energy consumption will also increase. These increases in baseload could potentially have a negative impact on the PFC of an operation, particularly with fixed PFC which is designed for a specific load and may lead to a decline in PF performance.

This highlights the importance of ensuring the PF remains stable above 0.96 by updating the PFC over time, especially when expanding the electrical network as operational demands increase. Other factors such as large variances in the load due to unexpected breakdowns or system switch-off can lead to a sudden decline in the PF performance and consequently increase the reactive energy consumption during standard and peak TOU.

In general, all the PODs saw a year-on-year increase in the average active power consumption, except for POD C1. This decline in the average kW consumption of POD C1 may be considered a sign of downscaling in terms of general production, optimisation of inefficient systems, or a combination of both.

Overall, the total excess reactive energy consumption of the 11 PODs saw a 12.27 GVarh reduction from 17.55 GVarh in 2021 to 5.28 GVarh in 2022. This equates to a 70% reduction in the year-on-year reactive energy consumption. The improved PF performance of the PODs, which led to the decrease in excess reactive energy consumption, may be attributed to the year-on-year reduction in capacitor bank downtimes.

The impact of the year-on-year reduced capacitor bank downtime on the average POD PF and excess reactive energy consumption is presented in Figure 64 and Figure 65.

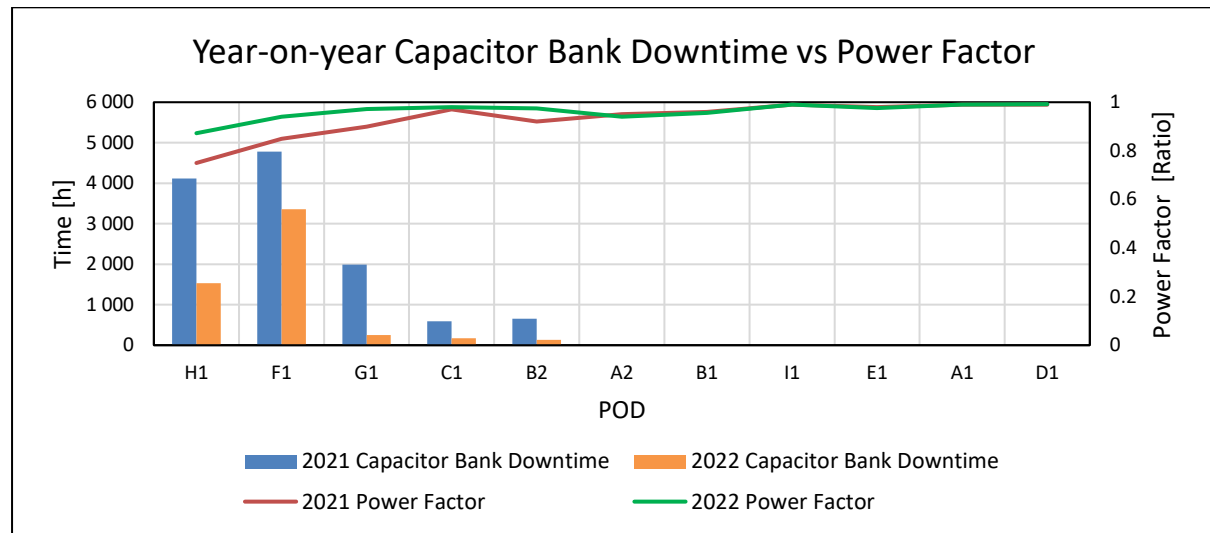


Figure 64: Case study post-implementation capacitor bank downtime impact on average power factor

The reduction in capacitor bank downtime correlates with the improved PF performance of the PODs as seen in Figure 64. It also corresponds with the reduced excess reactive energy consumption as presented in Figure 65.

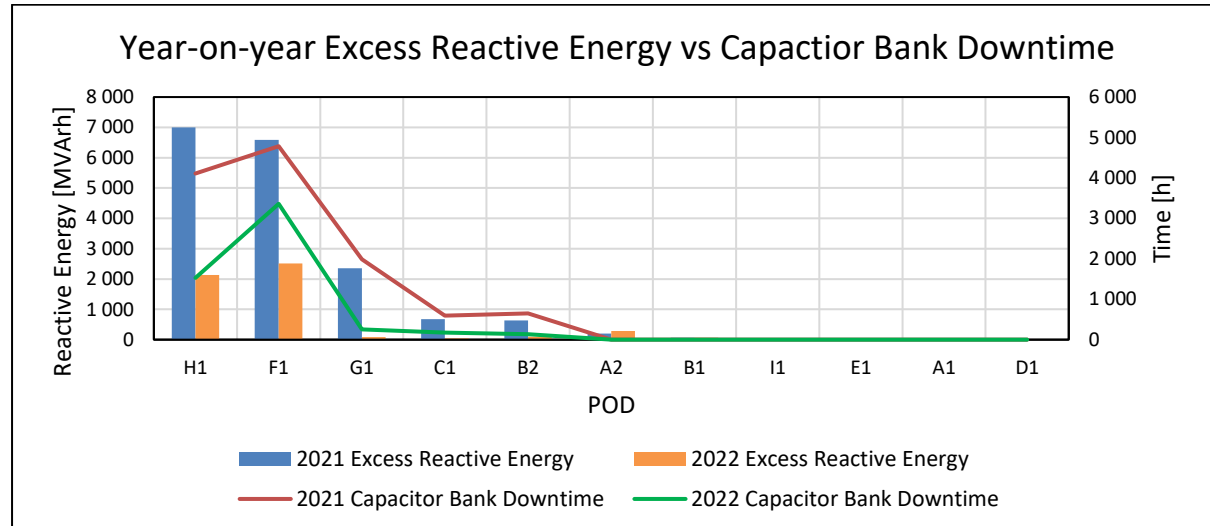


Figure 65: Case study post-implementation capacitor bank downtime impact on excess reactive energy

All the PODs (H1, F1, G1, C1, and B2) that experienced capacitor bank downtime in 2021 saw reduced downtime after the PFM tools were implemented in 2022. The largest improvement in capacitor bank downtime was realised on POD H1 with an estimated reduction of 2 584 hours along with an improvement in the average PF from 0.75 to 0.87 as seen from Figure 64. This resulted in POD H1 achieving the largest excess reactive energy consumption reduction of 4.87 GVarh as observed in Figure 63 and Figure 65.



The average PF performance of POD F1 improved from 0.85 to 0.94 post-implementation. However, the excess reactive energy consumption of POD F1 was higher than that of POD H1, although the average PF of POD F1 was higher. This can be attributed to the higher capacitor bank downtime of POD F1.

The capacitor bank downtime of POD F1 was estimated at 3 359 hours while for POD H1 it was 1 529 hours in 2022. This equates to an estimated downtime which is more than double that observed by POD H1. Furthermore, POD F1 has a higher power demand. This is evident when examining the average active power consumption of the PODs in 2022 and the maximum apparent power consumption, as presented in Table 33 and Figure 66 respectively. This higher power demand will typically lead to larger accumulation of reactive energy consumption when the POD PF drops below the limit of 0.96.

Figure 66 showcases the year-on-year impact of the PF performance on the maximum apparent power consumption of the various case study PODs.

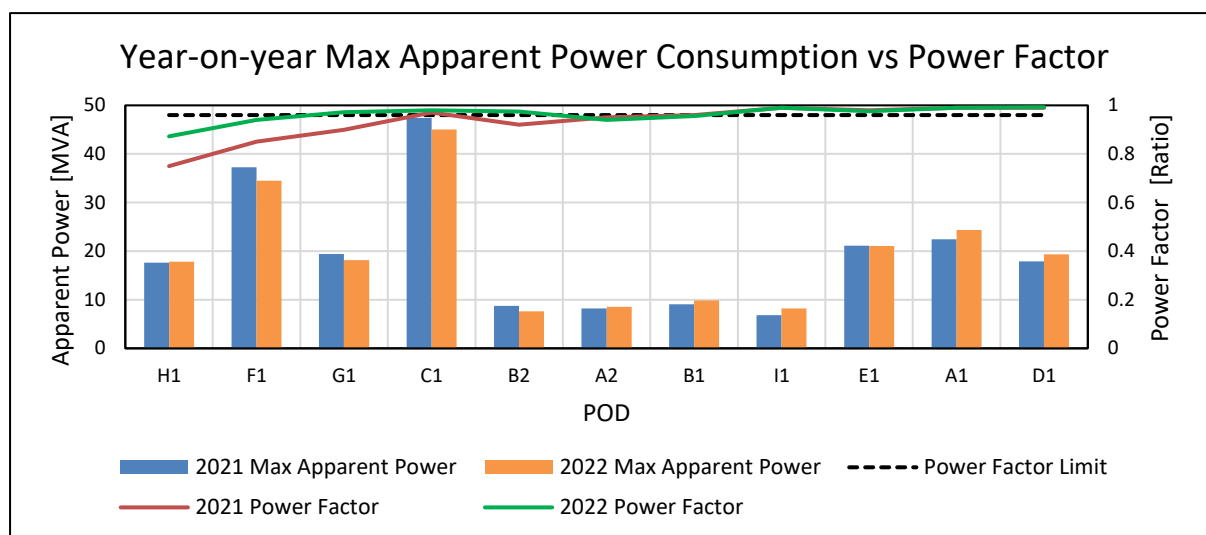


Figure 66: Case study post-implementation power factor impact on max apparent power consumption

It is evident from Figure 66 that PODs F1, G1, C1, and B2 experienced a year-on-year reduction in the maximum apparent power consumption recorded on the Eskom electricity bill. This can be attributed to the improved PF performance of the PODs in 2022. This is a noteworthy improvement when considering almost all the PODs, except for POD C1, saw an increase in year-on-year active power consumption as seen from Table 33.

PODs A2, B1, I1, A1, and D1 saw an increase in the maximum apparent power consumption with a similar year-on-year PF performance. This occurrence can be attributed to the increase in the average active power consumption of the PODs as presented in Table 33.



Although POD H1 saw an improvement in PF performance and a reduction in excess reactive energy consumption, a slight increase in the maximum apparent power consumption was observed. This can be attributed to the maximum apparent power consumption being recorded during a period where capacitor bank downtime was experienced. The maximum apparent power consumption recorded was 17.8 MVA at a PF of 0.72.

The increases and decreases in the maximum apparent power consumption of the PODs is also reflected in the excess apparent power consumption recorded at maximum demand. This can be observed when examining Figure 67, which compares the PF performance against the excess apparent power consumption.

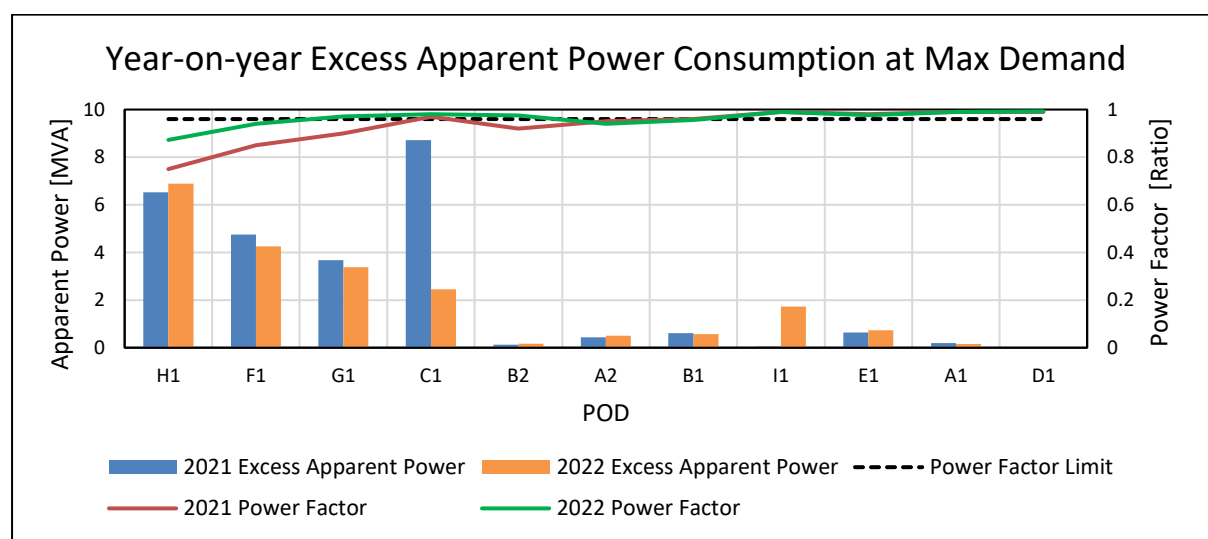


Figure 67: Case study post-implementation power factor impact on excess apparent power consumption

PODs F1, G1, C1, and B2 experienced a year-on-year reduction in the excess apparent power consumption due to improved PF performance similar to the maximum apparent power consumption performance observed in Figure 66.

POD C1 saw a relatively large decrease in the year-on-year excess apparent power consumption when compared to other PODs. This can be attributed to improved PF performance. The maximum apparent power consumption recorded in 2021 was measured at a PF of 0.82 during a period of capacitor bank downtime, while in 2022 it was measured at a PF of 0.95. This resulted in a 6.26 MVA (72%) reduction in excess apparent power consumption recorded at the maximum demand.

An increase in year-on-year excess apparent power consumption recorded at the maximum demand of POD H1 was observed in Figure 67. The excess apparent power consumption was recorded during capacitor bank downtime in both 2021 and 2022; however, the maximum



demand was measured in 2022 at a PF of 0.72 while in 2021 it was measured at a PF of 0.75, accounting for a higher excess apparent power consumption being recorded in 2022.

A considerable increase in the excess reactive energy consumption at maximum demand was observed at POD I1. This occurrence can be attributed to a large deviation in the power consumption over a short period of time, which is typically a sign of maintenance being conducted on a large system. The active power consumption of POD I1 increased by 3.64 MW within a 30-minute period.

The average PF of POD I1 was 0.79 at which the maximum apparent power consumption was recorded. This resulted in an excess apparent power consumption of 1.73 MVA being registered at the maximum recorded demand. The window of reduced PF performance was around 2.5 hours. This could be an indication of potential maintenance on the capacitor banks during this period. In general, large deviations in the power consumption can lead to reduced PF performance, especially on fixed PFC systems which are typically designed for a specific load.

A summary of the year-on-year electricity costs associated with the PF performance in terms of the excess reactive energy, maximum apparent power consumption, and excess apparent power consumption is outlined in Figure 68.

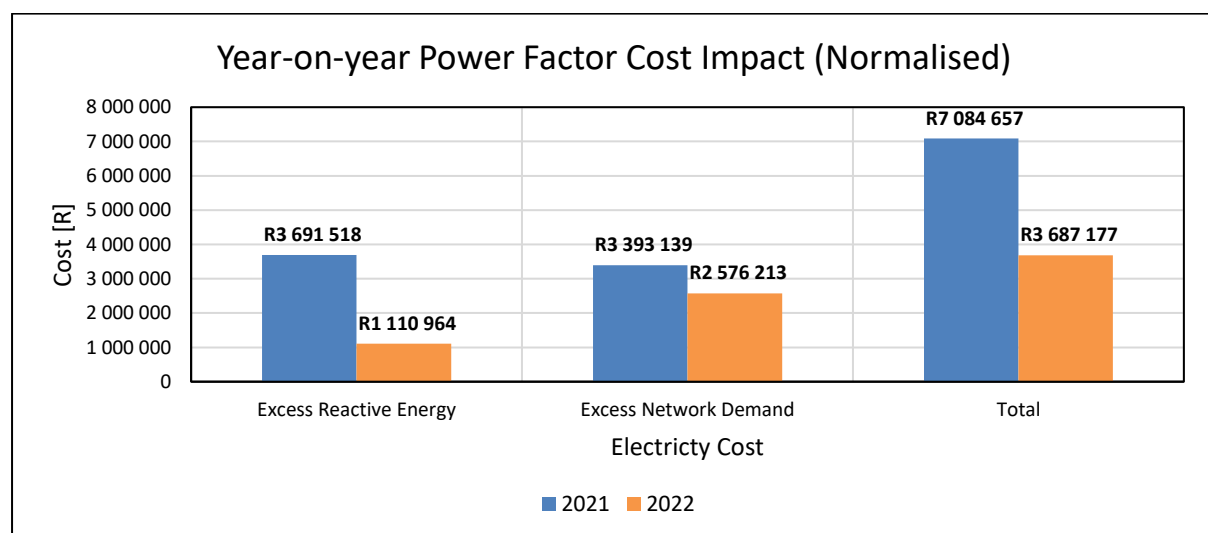


Figure 68: Case study post-implementation power factor cost impact (normalised)

Figure 68 presents the total electricity costs of the performance metrics outlined in Table 32. The 2021 costs were normalised (actual 2021 energy and power values multiplied by the 2022 applicable tariff) to allow a direct comparison between year-on-year costs.



The year-on-year normalised excess reactive energy charges across the 11 case study PODs decreased by R2.58 million (70%) due to the improved PF performance facilitated by reduced capacitor bank downtime. The largest contributors to these cost savings were PODs H1 (R1 million), F1 (R0.85 million), and G1 (R0.47 million).

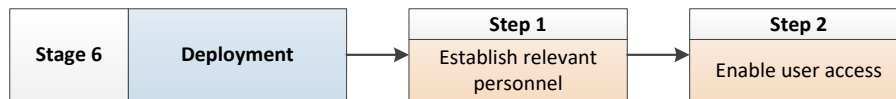
The reduction in excess reactive energy costs was combined with a normalised R0.81 million (24%) reduction in the total excess network demand charges due to the reduction in the total excess apparent power consumption recorded at maximum demand across the June to September Eskom billing period. This reduction in excess network demand charges attributed to the reduction in total network demand charges with a normalised year-on-year reduction of R0.98 million across the 11 PODs.

Overall, the combined PF cost impact on the excess reactive energy charges and excess network demand charges reduced from a normalised R7.08 million in 2021 to R3.68 million in 2022. This equates to a normalised year-on-year reduction of R3.4 million on the electricity costs within the June to September Eskom billing period.

In conclusion, the total capacitor bank downtime across the 11 case study PODs reduced by an estimated 6 683 hours (55%) with the implementation of the PFM tools, in fulfilment of Objective V. This resulted in an overall improvement in the average POD PF performance, which translated to combined normalised year-on-year electricity cost-savings of R3.4 million, in fulfilment of Objective VI. The PFM tools are, therefore, considered validated based on the reduced capacitor bank downtime, improved PF performance, and electricity cost-savings detailed in Section 3.2.6.3.

The 2021 and 2022 PF performance profiles of the case study PODs are presented in Appendix I.

3.2.7 Stage 6: Deployment



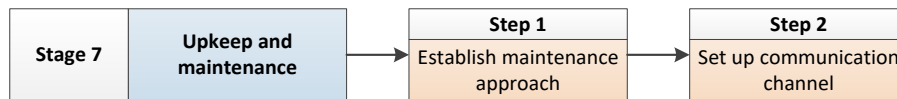
The PFM tools were deployed for use after being verified and validated in Section 3.2.6.3. As discussed in Section 2.7, the deployment process involves enabling user access to the monitoring, reporting, and notification tools. The tools were designed to be integrated and accessed via the MTB platform to which the case study mine group has access, as outlined in Section 2.4. Subsequently, this simplified the implementation and integration of the tools due to the familiarity of the MTB platform with the relevant mine personnel.

The personnel responsible for maintaining the installed PFC equipment and those involved in energy management were considered. The typical employee designations that were included comprise:

- Shaft engineer – responsible for managing and maintaining all the major systems.
- Electrical foreman – responsible for managing and maintaining all electrical systems.
- Electrician – responsibilities include routine inspection of capacitor banks.
- Energy management engineer – responsible for managing energy usage.
- Energy management contractors – responsible for managing energy usage.

Access to the tools was managed on each operation by consulting the shaft engineer to ensure all relevant onsite and offsite personnel gained access with the aim of facilitating increased awareness to enable proactive action to be taken when poor PF performance is identified. This has the added advantage of spreading the responsibility across multiple personnel to potentially reduce the risk of issues being left unattended.

3.2.8 Stage 7: Upkeep and maintenance



The upkeep and maintenance stage of the SDLC was initiated after the PFM tools were successfully deployed for use across the case study mine group. As discussed in Section 2.8, during this final stage of the SDLC, the tools will be maintained and upgraded over the remaining lifespan. This is done to ensure the tools remain operational, perform as expected, and are continually updated to meet the requirements of the users until the tools become obsolete.

Subsequently, this stage of the SDLC typically persists the longest and is responsible for consuming a major portion of the financial resources and is, therefore, seen as an important project consideration and should not be neglected.

The main types of maintenance that may be encountered during the lifespan of the tools are outlined in Section 2.8 and described by ISO/IEC/IEEE. This will be considered alongside the implementation of the IEEE standard for software maintenance as summarised in Figure 20.

The importance of an effective communication channel with the user is evident when examining the maintenance process outlined in Section 2.8. A designated line of communication was established in partnership with the case study mine group to allow for effective communication regarding maintenance and upkeep.

Furthermore, monthly meetings will be scheduled with relevant personnel to report and revise the impact of the PFM tools and to communicate potential issues or changes over the remaining lifespan. Performance tracking will also be implemented based on the key performance metrics and will be accomplished by comparing the progressive year-on-year PF performance of the various operations using Table 31 and Table 32.

3.3 Post-deployment review

The PF monitoring, reporting, and notification tools were officially deployed during the high-demand season of 2023. The tools are currently employed to facilitate the PF monitoring and management of 33 PODs across the various deep-level mine operations of the case study mine group.

A POD PF tracking sheet is used to follow up regarding the identification of reduced PF performance at the various PODs until the performance has been restored. The sheet is updated weekly based on the latest feedback from relevant site personnel regarding the investigations. Monthly meetings are held with the energy management engineer of the case study mine group to revise the PF performance and potentially expedite ongoing investigations. An example of the POD PF tracking sheet is included in Appendix J.

A POD PF limit sheet is also employed to keep track of changes to the POD limits as well as why these changes were implemented. It is important to keep the limits up to date, as the PF performance of the PODs may change over time due to system adjustments such as downscaling or expansion; therefore, helping to improve the accuracy of the limits based on the latest POD performance. An example of the POD PF limit sheet is included in Appendix J.

The normalised performance for the financial year of 2024 (June 2023 to September 2023) indicates a reduction of R9.1 million in the total reactive energy charges compared to the high-demand season performance of 2021 for the case study mine group, validating the use of the tools to improve PFM on deep-level mines through monitoring and reporting.

Minimal data issues were encountered during the deployment period. However, it is recommended to promptly investigate data loss and data anomalies, as this could be a sign of instrumentation issues. This could negatively affect the identification of poor PF performance and capacitor bank downtime, as the tools will not be able to accurately reflect the PF performance.

The case study mine group still has significant scope to further enhance the PF performance across the various operations. This may be achieved by modernising outdated PFC systems and by implementing PFC systems at operations that currently lack them. In turn, this could lead to a substantial reduction in the annual reactive energy charges and demand charges when combined with the PFM tools.

Furthermore, the PF notifications could also be extended to the individual incomers of the PODs to add an additional layer to the notification system. The identification of capacitor bank

downtime can be further improved if power consumption data was available to track whether the individual capacitor banks are active. A notification could then be set up to trigger based on the power consumption of the PFC systems and not only based on the PF performance data. These additional layers could also be integrated into the PF monitoring and reporting tools.

The aforementioned issues and improvements should be investigated during the upkeep and maintenance stage, as it is vital to strive for continuous improvement due to the ever-increasing electricity costs.

3.4 Conclusion

The waterfall SDLC methodology, as described in Chapter 2, was applied in Chapter 3 through an actual case study gold mine group to develop and implement PFM tools. The methodology was initialised in Section 3.2.2 via a performance analysis of various case study PODs based on the designated performance metrics outlined in Section 2.2. The goal of the performance analysis was to establish the current PF performance of PODs with PFC installed. These PODs were then ranked to identify which PODs need to be prioritised for improved performance.

The *5WH* framework was utilised in Section 3.2.3 during the requirements gathering and analysis stage of the SDLC to process the insights gathered from the case study performance analysis. The *5W* questions were used to process the problem and determine the requirements of the tools to be developed while the resulting requirements were subjected to a requirements analysis via the *H* question (“How?”) of the *5WH* framework. The list of tools and features were derived from the requirements analysis while also considering the background information from Chapter 1 and the performance metrics of Section 3.2.2.

The design specifications of the subsequent list of tools and features were defined in Section 3.2.4 with the aim of satisfying the requirements outlined in Section 3.2.3.1. The PFM tools were developed during Section 3.2.5 based on the designated features and design specifications. During the development stage, the design concepts were converted into working products to address the documented requirements.

The resulting tools were subjected to verification and validation in Section 3.2.6. The tools were verified using real-world data from the case study mine group to determine the output accuracy. This was achieved by examining the percentage error and MAPE of the tools when compared to the expected output generated from Excel. The tools were validated through real-world implementation on 11 case study PODs across 9 deep-level mine operations within the

2022 June to September Eskom billing period. The tools enabled improved PFM which resulted in a combined R3.4 million reduction (year-on-year normalised) in reactive energy charges and excess demand charges during the implementation period, satisfying the intended purpose of improving PFM on deep-level mines.

The deployment of the tools was discussed in Section 3.2.7, where relevant personnel were given access to the PF monitoring, reporting, and notifications tools for daily use. The upkeep and maintenance stage (final stage of the SDLC) was initiated after the tools were deployed and was discussed in Section 3.2.8. The IEEE standard for software maintenance, as described in Section 2.8, will be employed until the tools become obsolete. All the study objectives outlined in Section 1.9 were satisfied in Chapter 3. Therefore, the study is deemed validated.

The findings from Chapter 3 indicate that the monitoring, reporting, and notification tools proved to be effective in improving the PFM of the case study PODs; thus, equipping deep-level gold mines with the ability to potentially reduce operational costs with regards to electricity and assisting Eskom by reducing the total demand during standard and peak TOU.

It should be noted that the potential exists to further improve the current PF performance by updating outdated PFC systems and equipping deep-level mine operations with PFC systems which have none installed. Additional enhancements of the tools should also be considered and investigated during the upkeep and maintenance stage to promote continuous improvement in PFM.

CHAPTER 4

4 CONCLUSION AND RECOMMENDATIONS

This final chapter provides a conclusive discussion regarding the study. A detailed summary of the study is presented in Section 4.1, while recommendations for future work pertaining to this study are discussed in Section 4.2.

4.1 Summary

The South African gold mining industry is faced with numerous challenges that influence profitability and long-term sustainability. The industry is one of the main consumers of energy in South Africa due to its intensive use of electricity. Electricity costs have become one of the major challenges faced by deep-level gold mines due to significant increases in the electricity tariffs over the past two decades.

The concerns regarding the ever-increasing electricity costs have been amplified in recent years due to Eskom's struggle to sufficiently meet the country's electricity demands. This has forced Eskom to resort to load management methods such as load shedding and load curtailment to reduce demand during peak TOU. Furthermore, Eskom allocates monthly penalties to consumers with power factors of 0.96 and less in the form of reactive energy charges. These charges are applicable throughout the high-demand season during peak and standard demand periods.

The total energy demand of a consumer is increased by excess reactive energy and leads to additional strain on the electrical grid. The reduction in excess reactive energy consumption is, therefore, essential in maintaining the stability of the energy supply. This, in turn, reduces the need for Eskom to resort to load curtailment, which negatively affects the productivity of electricity-intensive consumers such as deep-level gold mines.

PFM on deep-level gold mines has become increasingly important to mitigate reactive energy charges and reduce overall demand to combat increased electricity costs and improve grid stability. Unfortunately, most mines rely on the monthly Eskom electricity bill to identify poor PF performance where it is made evident through reactive energy charges. This can be attributed to a lack of access to tools that enable the monitoring and identification of reduced PF performance. Therefore, a need exists to improve PFM on deep-level gold mines to not only reduce electricity costs, but also to ease the strain on Eskom's electricity generation capacity.

Further background knowledge was obtained in Chapter 1 by investigating the Eskom electricity tariff structures, the fundamentals of power factors and their impact on deep-level

mines. PFC and the existing PFM on South African mines were explored, alongside potential PFM tools.

Previous research studies were reviewed in Section 1.7 to investigate the current PFM approach applied in industry and the latest technologies being utilised. Past literature indicated that the majority of studies only relied on monitoring the power factors as part of their PFM approach, whilst only a handful of studies investigated the implementation of web-based tools and smartphone integration. The utilisation of a notification system to inform personnel regarding poor PF performance was neglected and only two studies explored power factors within the mining industry, further substantiating the need for this study.

This study, therefore, focused on developing monitoring, reporting, and notification tools that can be utilised to facilitate improved PFM on deep-level gold mines with existing PFC equipment. The design and development of the tools focused on utilising existing infrastructure and integrating the tools to platforms already accessible to the mine to reduce implementation costs and mitigate accessibility issues. The following objectives were formulated based on the need for the study, derived from the background knowledge and research conducted in Chapter 1:

- I. Establish the PF performance of various deep-level mine operation PODs.
- II. Rank and prioritise deep-level mine operation PODs for PF improvement based on power factors, demand charges, and reactive charges.
- III. Develop and implement PF monitoring, reporting, and notification tools:
 - a. Web-based monitoring and data visualisation of power factors.
 - b. Daily performance report on historic PF performance.
 - c. Notification system to warn personnel of poor power factors.
- IV. Develop and implement the tools by utilising existing platforms available to the deep-level mine operations.
- V. Reduce capacitor bank downtime by means of earlier fault detection.
- VI. Reduce annual penalties on reactive energy charges and demand charges.

The waterfall SDLC methodology was utilised for the development of the PFM tools. It is a stepwise approach where each stage needs be completed in sequence before progressing to the next stage. It is one of the most widely used system/solution development methodologies and was selected due to its simplicity, ease of implementation, and proven track record. The methodology outlines the entire system development life cycle from problem identification and requirements gathering to deployment and maintenance. Each stage of the methodology was discussed in Chapter 1, Section 1.10.3, and further elaborated on in Chapter 2.

The methodology was applied in Chapter 3 on a case study gold mine group to develop and implement PFM tools. The first step was to conduct a performance analysis of various case study mine operation PODs by investigating the designated performance outlined in Section 2.2. The analysis examined the performance of 11 PODs from the case study mine group within the Eskom high-demand season (June to September billing period of 2021) in fulfilment of Objective I. These PODs were ranked based on performance, in fulfilment of Objective II, to establish which PODs need to be prioritised for improved PF performance.

In total, R3.09 million in penalties on reactive energy consumption was identified along with R3.36 million in excess network demand charges during the performance analysis period. These costs can be attributed to substantial capacitor bank downtime (estimated 12 130 hours) which in turn reduced the PF performance of the case study PODs during standard and peak TOU, thereby indicating significant potential to improve the current PFM of these PODs while also achieving noteworthy savings on electricity costs.

The insights gathered from the performance analysis were processed during the requirements gathering and analysis stage via the *5WH* framework. The requirements were established and subjected to a requirements analysis from which the list of tools and features were derived. The knowledge obtained from Chapter 1 and the performance metrics of Section 2.2 were also considered during this process.

The design specifications of the PFM tools, with their respective features, were defined during the design stage based on the set requirements. The design concepts (designated features and design specifications) were converted into working tools to address the documented requirements during the development stage in partial fulfilment of Objectives III and IV.

The developed tools were verified by examining the output accuracy of the tools via real-world data from the case study mine group. The output of the tools was compared to the expected output generated in Excel. The accuracy was established by investigating the resulting error percentage and MAPE values from the output comparison, from which the tools were deemed verified.

The tools were subjected to validation after the verification process concluded. The validation process comprised implementing the tools on 11 case study PODs across 9 deep-level mine operations, in fulfilment of Objectives III and IV. The performance of the tools were examined within the 2022 June to September Eskom billing period. A combined R3.4 million (year-on-year normalised) reduction in reactive energy charges and excess network demand charges were achieved during the implementation period across the 11 case study PODs.

This was achieved due to the PFM tools contributing to an estimated 6 683 hours (55%) reduction in capacitor bank downtime owing to earlier fault detection. This, in turn, led to a R2.58 million (70%) reduction (year-on-year normalised) in reactive energy charges and R0.81 million (24%) reduction (year-on-year normalised) in excess network demand charges due to improved POD PF performance. From these results, it is evident that Objectives V and VI have been met.

The tools were deployed for official use on the case study mine group after being verified and validated. During this stage, relevant personnel were given access to the PF monitoring, reporting, and notifications tools for daily use. With the tools deployed and active, the upkeep and maintenance stage (final stage of the SDLC) was initiated. The IEEE standard for software maintenance will be employed during this stage until the tools become obsolete. Monthly meetings will be conducted to acquire user feedback and track performance.

The study concludes that the implementation of daily PF monitoring, reporting, and notification tools proved to be effective in improving the PFM on deep-level mines. The tools facilitated in achieving reduced capacitor bank downtime through earlier fault detection, providing deep-level mines with the ability to reduce penalties on excess reactive energy consumption and excess network demand costs.

Furthermore, Eskom also benefits from the reduced electricity demand during standard and peak TOU which, in turn, helps to improve the stability of the electrical grid, reducing the need for Eskom to resort to load management methods such as load shedding and load curtailment.

However, where feasible, adequate PFC initiatives should be implemented alongside these tools to obtain optimal results. This will further improve PFM by assisting in the realisation of sustained improvement in PF performance. Therefore, the potential to improve the tools should be further explored during the upkeep and maintenance stage.

4.2 Recommendations for future work

The purpose of this section is to provide recommendations for future work pertaining to this study to potentially improve on the obtained results and explore the expansion of the tools for other uses.

Expand the performance analysis period to include the summer months.

The examination period used to establish the impact of the tools on PF performance was limited to the Eskom high-demand season (June to September billing periods). Although there are no penalties allocated on reactive energy consumption during the summer months, the PF performance still influences the maximum demand (kVA) during this period. The analysis period should, therefore, be extended to include the summer months (October to May Eskom billing periods) to establish the total impact on the network demand charges which are billed throughout the year.

Furthermore, the analysis could be extended to examine the reduction in risk of PODs exceeding their NMD due to improved PFM. The penalties on exceeding the NMD are expensive, as they are multiplied by the number of times the NMD has been exceeded, as outlined in Appendix C (Figure 81). This could have a substantial impact in the case where a deep-level mine operation is faced with a situation where additional system capacity is required to maintain operation stability over a prolonged period. When this is combined with poor PF, it could potentially increase the risk of exceeding the POD NMD and lead to additional unwanted costs.

Expand power factor notifications and reporting tools to include incomers.

Currently, only the PF monitoring and data visualisation tool utilises data of the incomers on the deep-level mine operations to identify the cause of reduced PF performance at a POD. This could be extended to the reporting and notifications tools. PF limits on the individual incomers can be set up and triggered to notify personnel of reduced PF performance. The power profiles of these incomers could then also be documented via the daily reporting tool.

The power data of the incomers of all the PODs are available. Therefore, this proposal for future work is already being incorporated into the notification tool as part of the maintenance stage and testing will commence in the near future.

Investigate power factor monitoring of individual systems.

The developed tools could be transitioned to monitoring the PF performance of individual systems connected to the incomers such as fridge plants, compressors, winders, ventilation fans, or pumps. A poor PF is an indication of inefficiencies in the system which may lead to performance issues, as outlined in Section 1.4.2. Therefore, potential underlying issues that may lead to breakdowns or a reduction in the lifespan of machines may be detected in advance and investigated.

Expand instrumentation to track power consumption and control of PFC systems.

Currently, there are no data tags available to monitor the power consumption of the PFC systems across the case study mine group. Therefore, the identification of capacitor bank downtime can be further enhanced with the ability to monitor the power consumption of the individual capacitor banks via the PFM tools. A notification could then be set up to trigger based on the power consumption of the PFC systems and not only based on the PF performance data for additional confirmation. This, in turn, may lead to earlier fault detection.

Furthermore, it might also be beneficial to investigate the use of instrumentation that could enable the monitoring of the control status of PFC systems specifically, dynamic PFC systems which can be set to manual or automatic control. There have been instances where reduced PF performance was identified and investigated only to discover the PFC control was set to manual and not automatic as intended. This typically occurs during maintenance where systems are usually set to manual control with the initial start-up, but personnel forget to reinstate automatic control. The general PF performance could potentially be improved by ensuring the PFC systems remain on automatic control to achieve optimal performance, especially at incomers where the base power load varies.

Update existing PFC systems or investigate the feasibility of installing PFC.

As discussed in Section 1.5.2, many large mining and industrial customers have outdated PFC systems. The PFC systems may become inadequate due to expansion of the electrical network or even due to downscaling. Some older operations do not have PFC systems that are operational due to a lack of maintenance and, therefore, become decommissioned. An investigation should, therefore, be conducted on the case study mine group to establish the potential benefit of modernising the existing PFC systems and installing PFC at older operations. This could further improve the PF performance and minimise penalties on reactive energy charges and network demand charges.

The latest PFC technologies should be investigated during this process. The potential use of mobile PFC systems could increase the feasibility of improving the PFC of older operations. These PFC systems could be relocated once an operation has reached its end-of-life to an operation that is planning to expand instead of having the PFC decommissioned. Therefore, the use of synchronous motors could also be investigated, particularly for machinery that typically run throughout the day such as compressors, ventilation fans, and fridge plants.

Expand tools to also monitor harmonic distortion.

Harmonic distortion is an important factor to consider alongside PFC systems, as it can drastically reduce the lifespan of capacitor banks as discussed in Section 1.5.1. Investigating the use of instrumentation to allow for the monitoring of harmonic distortion may prove to be valuable in the longevity of existing PFC systems. The harmonic distortion present in the electrical network may change over time as the electrical network is modified due to expansion or downscaling. Therefore, integrating the ability to monitor harmonic distortion in future iterations of the PFM tools should be considered. This may enable proactive action to be taken to have the correct harmonic filtering installed to improve PFC performance.

Improve the general accessibility of the tools.

One of the objectives of the study was to develop and integrate the tools with the existing infrastructure and platforms available to deep-level mines. This influenced the selection of the software used to create and implement the tools with the case study mine group. Although Power BI is available to the public, the access to the performance reporting and notification tools is limited.

The general accessibility of the tools can, therefore, be further improved by exploring software products that are more accessible. Various BI software products are listed in Table 10 and free BI tools are presented in Appendix G that could potentially be utilised to achieve the same functionalities of the tools developed in this study.

Investigate the potential impact of renewable energy generation on PFC.

There has been a large drive towards the implementation of renewable energy sources across the world in recent years, particularly the installation of large grid-tied PV systems. Large energy consumers such as the mining industry are also targeting the installation of large PV systems to combat the ever-increasing electricity costs and to strive towards becoming carbon neutral to minimise carbon taxes.

As stated by [54] in Section 1.7.3, standard PV systems may negatively impact the overall PF performance of an electrical system and lead to potential penalties on reactive energy consumption. Therefore, alongside the implementation of PFM tools, corrective measures should also be investigated and implemented with the installation of large grid-tied PV systems in the mining industry to ensure optimal PFC performance.

Investigate the use of a clocking and accountability system for daily PFC inspections.

One of the daily duties of the electricians on the mines are to inspect the status of the PFC systems. This is often neglected, which can lead to prolonged periods of reduced PF performance when PFC systems such as capacitor banks trip and remain inactive until reinstated.

Therefore, the implementation of a clocking system to track whether an electrician completed their daily inspection of the PFC systems should be considered. Furthermore, an accountability system can be incorporated by having the electricians provide an explanation via a daily report in the event of the PFC system not being inspected. The aforementioned suggestions could assist in reducing capacitor bank downtime and earlier fault detection.

Explore the use of the developed tools in other industries.

The implementation of the tools developed in this study could also be explored in other energy-intensive industries such as:

- Iron and steel manufacturing,
- cement and concrete manufacturing,
- chemical and petrochemical manufacturing, and
- food and beverage products.

The stability of the Eskom electrical grid and the overall efficiency of industrial operations may benefit greatly by investing in improved PFM based on the results achieved within this study.

5 REFERENCES

- [1] DMRE, 'The South African Energy Sector Report 2021', Pretoria, Republic of South Africa, 2021. Accessed: Aug. 10, 2022. [Online]. Available: <http://www.energy.gov.za/files/media/explained/2021-South-African-Energy-Sector-Report.pdf>.
- [2] P. Peach, 'Optimising deep-level mine refrigeration control for sustainable cost savings', M.Eng. Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.
- [3] L. van der Zee and R. Pelzer, 'Modelling of electricity cost risks and opportunities in the gold mining industry', Ph.D. Thesis, School of Electronic Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [4] J. Marais and M. Kleingeld, 'An integrated approach to optimise energy consumption of mine compressed air systems', Ph.D. Thesis, School of Electrical Engineering, North-West University, Potchefstroom, 2012.
- [5] J. I. G. Bredenkamp, M. J. Mathews, and J. C. Vosloo, 'An integrated energy management strategy for the deep-level gold mining industry', in *Proceedings of International Conference on the Industrial and Commercial Use of Energy (ICUE)*, 2016, pp. 133–138.
- [6] J. Schmidt-Whitley and N. Sutorius-Lavoie, 'Mining And Mineral Processing: Remains Vital for African Economy', *Engineering and Mining Journal*, vol. 205, no. 5, pp. 21–30, 2004.
- [7] J. Jonker, 'Automated mine compressed air control for sustainable savings', M.Eng. Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2016.
- [8] A. Salama, M. Nehring, and J. Greber, 'Financial analysis of the impact of increasing mining rate in underground mining, using simulation and mixed integer programming', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 117, no. 4, pp. 365–372, 2017.
- [9] P. N. Neingo and T. Tholana, 'Trends in productivity in the South African gold mining industry', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 116, no. 3, pp. 283–290, Mar. 2016, doi: 10.17159/2411-9717/2016/V116N3A10.

- [10] P. Peach, M. Kleingeld, and J. I. G. Bredenkamp, 'Optimising deep-level mine refrigeration control for sustainable cost savings', in *Proceedings of International Conference on the Industrial and Commercial Use of Energy (ICUE)*, 2017, pp. 1–8.
- [11] H. Trollip, A. Butler, J. Burton, T. Caetano, and C. Godinho, 'Energy Security in South Africa', *Mitigation Action Plans and Scenarios (MAPS)*, no. 17, pp. 1–32, 2014.
- [12] S. S. Routray, 'Microcontroller based automatic power factor correction in mines', M.Tech. Dissertation, School of Mining Engineering, National Institute of Technology, Rourkela, India, 2015.
- [13] W. H. Sang, 'Time-Of-Use Rates And Load Management In The Water Industry: Cost Savings Or Energy Conservation?', in *Proceedings of ENERGEX '84, The Global Energy Forum*, F. Curtis, Ed., Regina, Saskatchewan, Canada, 1984, pp. 783–788, doi: 10.1016/B978-0-08-025407-4.50140-X.
- [14] Leonardo Energy, '*Electric Load Management in Industry*', Paris, France, 2009. Accessed: Aug. 20, 2022. [Online]. <https://www.leonardo-energy.pl/wp-content/uploads/2017/08/Electric-Load-Management-in-Industry.pdf>.
- [15] M. A. Kassem and A. A. Elahwil, 'Power Load Management Techniques and Methods in Electric Power System', *International Research Journal of Engineering and Technology*, vol. 02, no. 09, pp. 2459–2466, 2015, issn: 2395-0072.
- [16] K. Al Khuffash, *Smart grids – Overview and background information., Application of Smart Grid Technologies: Case Studies in Saving Electricity in Different Parts of the World*, L. Lamont and A. Sayigh, Eds., London, Academic Press, 2018, pp 1–10.
- [17] W. Hamer, 'Analysing electricity cost saving opportunities on South African gold processing plants', M.Eng. Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [18] C. J. Boshoff, 'Evaluation and implementation of DSM strategies to improve the profitability of marginal cement grinding plants', M.Eng. Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2015.
- [19] J. de Wet, 'Load management through the utilisation of VSDs on water transfer schemes', M.Eng. Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2017.

- [20] Eskom, '*Tariffs and Charges Booklet 2022/2023*', South Africa, 2022. Accessed: Jun. 10, 2022. [Online]. Available: https://www.eskom.co.za/distribution/wp-content/uploads/2022/05/20220504_4756-ESKOM-Tariff-Booklet-2022-Final2.pdf.
- [21] C. Pan, 'Joint CSP and PV power plant simulation – enabling economic power production through combined operation', PhD Thesis, School of Mechanical and Mechatronic Engineering, Stellenbosch University, Stellenbosch, South Africa, 2015.
- [22] S. Irshad, '*Electrical System - Bureau of Energy Efficiency*', Anantapur, India, 2008. Accessed: Apr. 24, 2022. [Online]. Available: https://www.academia.edu/40869365/ELECTRICAL_SYSTEM_1_Bureau_of_Energy_Efficiency.
- [23] Eskom, '*Correcting your power factor*', South Africa, 2020. Accessed: Aug. 26, 2022. [Online]. Available: <https://www.eskom.co.za/eas/wp-content/uploads/2021/05/POWER-FACTOR-TECHNICAL-OVERVIEW.pdf> (accessed Aug. 26, 2021).
- [24] Eskom, '*Notification of demand or changes to notified maximum demand (NMD) rules index of rules*', South Africa, 2009. Accessed: Aug. 13, 2023. [Online]. Available: https://www.eskom.co.za/distribution/wp-content/uploads/2021/08/Notified-maximum-demand-rules-_Rev02.pdf.
- [25] A. Bhatia, '*Power Factor in Electrical Energy Management*', E144, 2012, *PDH Online*, New York, Accessed: Aug. 26, 2021. [Online]. Available: <https://www.pdhonline.com/courses/e144/e144content.pdf>.
- [26] NHP, '*Power Factor Correction - Power Quality Catalogue*', Australia, 2007. Accessed: Aug. 27, 2021. [Online]. Available: <https://cpa-ltd.net/wp-content/uploads/2021/05/Introduction-to-Power-Factor-Correction.pdf>
- [27] ABB, '*Power factor correction and harmonic filtering in electrical plants*', Bergamo, Italy, 2008, Accessed: Aug. 27, 2021. [Online]. Available: https://d2z8ufzpcqvblm.cloudfront.net/sites/www.voltimum.co.uk/files/fields/attachment_file/gb/flipbooks/others/K/201201119822.pdf.
- [28] J. Ware, '*Power Factor Correction*', IEE Wiring Matters, 2006. Accessed: Sep. 03, 2022. [Online]. Available: <https://electrical.theiet.org/media/1687/power-factor-correction-pfc.pdf>.

- [29] D. Pudney, 'Designing power factor correction equipment for economic returns'. Energize, South Africa, 2010, Accessed: Sep. 17, 2022. [Online]. Available: <https://www.scribd.com/document/671037363/Designing-Power-Factor-Correction-Equipment-for-Economic-Returns>.
- [30] H. Visser, 'Some cost implications of electric power factor correction and load management', M. Phil. Dissertation, School of Engineering Management, University of Johannesburg, Johannesburg, South Africa, 2001.
- [31] M. Stangl, J. Pielmeier, C. Berger, S. Braunreuther, and G. Reinhart, 'Development of a Web Based Monitoring System for a Distributed and Modern Production', *Procedia CIRP*, vol. 52, pp. 222–227, 2016, doi: 10.1016/J.PROCIR.2016.07.073.
- [32] D. S. Dorr, 'Point of utilization power quality study results', *IEEE Transactions on Industry Applications*, vol. 31, no. 4, pp. 658–666, 1995, doi: 10.1109/28.395270.
- [33] D. O. Koval and M. B. Hughes, 'Canadian National Power Quality Survey: frequency of industrial and commercial voltage sags', *IEEE Transactions on Industry Applications*, vol. 33, no. 3, pp. 622–627, 1997, doi: 10.1109/28.585850.
- [34] B. Byman, T. Yarborough, R. Schnorr Von Carolsfeld, and J. Van Gorp, 'Using distributed power quality monitoring for better electrical system management', *IEEE Transactions on Industry Applications*, vol. 36, no. 5, pp. 1481–1485, 2000, doi: 10.1109/28.871298.
- [35] T. L. Baldwin, 'Tools for supplying premium quality power', in *Proceedings of IEEE Technical Applications Conference and Workshops*, 1995, pp. 288–293, doi: 10.1109/NORTHHC.1995.485085.
- [36] S. A. E. L. Perera, W. R. A. Fonseka, I. Samaradiwakara, N. D. M. Withanage, and H. K. U. Wijekantha, 'Web Based Network Monitoring System', B.Sc. Special Honors in Information Technology Specialized in Systems and Networking, Department of Information Technology, Sri Lanka Institute of Information Technology, Colombo, Sri Lanka, 2012.
- [37] Treasury Board Secretariat, 'Performance Reporting Principles and Guidelines', Manitoba, Canada, 2008. Accessed: Sep. 20, 2022. [Online]. Available: https://www.manitoba.ca/finance/tb/pubs/performance_reporting_guide.pdf.

- [38] P. K. Lee, L. L. Lai, and S. W. Chan, 'A practical approach of energy efficiency management reporting systems in micro-grid', in *Proceedings of IEEE Power and Energy Society General Meeting*, 2011, pp. 1–5, doi: 10.1109/PES.2011.6039580.
- [39] N. R. Tague, 'The Tools', in *The Quality Toolbox*, 2nd ed., A. Hytinen and P. O'Mara, Eds., Milwaukee, Wisconsin, United States of America: ASQ Quality Press., 2005, ch. 5, pp. 155–196.
- [40] D. Noskievičová, M. Mahdal, and K. Brodecká, 'SW support for CCC and CQC control charts', in *Proceedings of the 15th International Carpathian Control Conference (ICCC)*, 2014, pp. 387–392, doi: 10.1109/CARPATHIANCC.2014.6843633.
- [41] D. C. Montgomery and G. C. Runger, 'Sampling Distributions and the Central Limit Theorem', in *Applied Statistics and Probability for Engineers*, 6th ed., Singapore: John Wiley & Sons, Ltd, 2014, ch. 7, pp. 237–243.
- [42] National Institute of Standards and Technology, 'Process or Product Monitoring and Control', in *NIST/SEMATECH e-Handbook of Statistical Methods*, U.S. Department of Commerce, 2015. Accessed: Sep. 23, 2022. [Online]. Available: <https://www.itl.nist.gov/div898/handbook/pmc/section3/pmc31.htm>.
- [43] J. Deng, C. S. Lam, M. C. Wong, L. Wang, S. W. Sin, and R. P. Martins, 'A power quality indexes measurement system platform with remote alarm notification', in *Proceedings of 44th Annual Conference of the IEEE Industrial Electronics Society*, Jul. 2018, pp. 3461–3465, doi: 10.1109/IECON.2018.8591375.
- [44] B. E. Kushare, A. A. Ghatol, and S. Kala, 'Development of web based power quality monitoring system for handling user custom power quality query and auto power quality monitoring report notification via email', in *Proceedings of IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES)*, 2007, pp. 1–7, issn: 0537-9989.
- [45] F. Roos and R. C. Bansal, 'Reactive power and harmonic compensation: A case study for the coal-mining industry', *Journal of Energy in Southern Africa*, vol. 30, no. 1, pp. 34–48, Mar. 2019, doi: 10.17159/2413-3051/2019/V30I1A2473.
- [46] K. Wahab, M. Rahal, and R. Achkar, 'Economic Improvement of Power Factor Correction: A Case Study', *Journal of Power and Energy Engineering*, vol. 09, no. 06, pp. 1–11, 2021, doi: 10.4236/jpee.2021.96001.

- [47] A. C. Ortega, F. J. Sánchez Sutil, and J. de la C. Hernández, 'Power factor compensation using teaching learning based optimization and monitoring system by cloud data logger', *Sensors (Switzerland)*, vol. 19, no. 9, pp. 1–23, May 2019, doi: 10.3390/S19092172.
- [48] T. A. Nguyen and R. H. Byrne, 'Optimal Time-of-Use Management with Power Factor Correction Using Behind-the-Meter Energy Storage Systems', in *Proceedings of IEEE Power and Energy Society General Meeting*, Dec. 2018, pp. 1–5, doi: 10.1109/PESGM.2018.8586022.
- [49] H.M.S. Herath, 'Power quality data management and reporting methodologies', PhD thesis, School of Electrical, Computer and Telecommunications Engineer, University of Wollongong, New South Wales, Australia, 2008.
- [50] S. New, B. Ramachandran, H. Nano, J. Havemann, Z. Wang, M. Posey, E. Hogan, K. Chu, D. McCormick, T. Youssef, 'Design and Implementation of a Real-Time Energy Monitoring and Reporting System', in *Proceedings of 51st North American Power Symposium (NAPS)*, Oct. 2019, pp. 1–6, doi: 10.1109/NAPS46351.2019.9000322.
- [51] R. Sen Biswas and S. Mal, 'Automatic power factor improvement using microcontroller', in *Proceedings of International Conference and Workshop on Computing and Communication*, Dec. 2015, pp. 1–6, doi: 10.1109/IEMCON.2015.7344500.
- [52] S. Khanchi and V. K. Garg, 'Power Factor Improvement of Induction Motor by Using Capacitors', *International Journal of Engineering Trends and Technology*, vol. 4, no. 7, pp. 2967–2971, 2013, issn: 2231-5381.
- [53] T. Adefarati, A. S. Oluwole, K. O. Olusuyi, and M. A. Sanusi, 'Economic and Industrial Application of Power Factor Improvement', *International Journal of Engineering Research and Technology (IJERT)*, vol. 2, no. 11, pp. 1945–1955, 2013, issn: 2278-0181.
- [54] P. Pachanapan, 'The control of large scale grid-tied photovoltaic rooftop systems to avoid the power factor charge', in *Proceedings of the International Conference on Power, Energy and Innovations (ICPEI)*, Oct. 2019, pp. 24–27, doi: 10.1109/ICPEI47862.2019.8944973.
- [55] S. Saha, T. Tyagi, and D. V. Gadre, 'ARM(R) microcontroller based automatic power factor monitoring and control system', in *Proceedings of the Texas Instruments India Educators' Conference (TIIEC)*, 2013, pp. 165–170, doi: 10.1109/TIIEC.2013.36.

- [56] D. C. Maheepala, R. M. N. Nayanajith, M. W. R. P. Somarathna, R. A. A. M. Bandara, and K. T. M. U. Hemapala, 'Designing an energy monitoring, analysing and solution providing system for energy auditing', in *Proceedings of 4th IEEE International Conference on Advances in Electrical and Electronics, Information, Communication and Bio-Informatics (AEEICB)*, Oct. 2018, doi: 10.1109/AEEICB.2018.8480953.
- [57] M. Longo, S. Franzo, V. M. Latilla, and G. Antonucci, 'Smart Energy Management of a Railway Station', in *Proceedings of IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Oct. 2018, doi: 10.1109/EEEIC.2018.8494481.
- [58] S. C. Gu, C. H. Cheng, and G. J. Jong, 'The power monitor system combined green energy', in *Proceedings of 1st International Future Energy Electronics Conference (IFEEEC)*, 2013, pp. 757–760, doi: 10.1109/IFEEEC.2013.6687603.
- [59] C. M. Coman, A. Florescu, and C. D. Oancea, 'Improving the Efficiency and Sustainability of Power Systems Using Distributed Power Factor Correction Methods', *MDPI Sustainability*, vol. 12, no. 8, pp. 1–20, Apr. 2020, doi: 10.3390/SU12083134.
- [60] F. Zheng and W. Zhang, 'Long term effect of power factor correction on the industrial load: A case study', in *Proceedings of Australasian Universities Power Engineering Conference (AUPEC)*, Nov. 2017, pp. 1–5, doi: 10.1109/AUPEC.2017.8282382.
- [61] L. Morales-Velazquez, R. de Jesus Romero-Troncoso, G. Herrera-Ruiz, D. Morinigo-Sotelo, and R. Alfredo Osornio-Rios, 'Smart sensor network for power quality monitoring in electrical installations', *Measurement*, vol. 103, pp. 133–142, 2017, doi: 10.1016/j.measurement.2017.02.032.
- [62] Y. Kabir, Y. M. Mohsin, and M. M. Khan, 'Automated power factor correction and energy monitoring system', in *Proceedings of 2nd IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, Nov. 2017, pp. 1–5, doi: 10.1109/ICECCT.2017.8117969.
- [63] M. A. Rahman, S. M. Tahsin, D. Das, and R. Chowdhury, 'Power factor Controlling and Monitoring wirelessly through computer', in *Proceedings of IEEE Region 10 Symposium (TENSYP)*, Jun. 2020, pp. 547–551, doi: 10.1109/TENSYP50017.2020.9230695.
- [64] S. Bayhan, S. Demirbas, and I. Garip, 'Internet based power quality monitoring system', in *Proceedings of International Conference on Power Engineering, Energy and Electrical Drives*, May 2013, pp. 453–456, doi: 10.1109/POWERENG.2013.6635650.

- [65] N. R. Kulkarni, H. Vijay Murthy, and A. P. Raju, 'PLC based intelligent power factor correctors for industrial power systems-A case study', in *Proceedings of IEEE International Conference on Power and Advanced Control Engineering (ICPACE)*, Sep. 2015, pp. 75–79, doi: 10.1109/ICPACE.2015.7274920.
- [66] I. Colak, R. Bayindir, H. T. Kahraman, S. Sagiroglu, I. Colak, and R. Bayindir, 'Power factor correction technique based on artificial neural networks', *Energy Conversion and Management*, vol. 47, no. 18–19, pp. 3204–3215, 2006, doi: 10.1016/j.enconman.2006.02.018.
- [67] A. A. A. Adenowo and B. A. Adenowo, 'Software Engineering Methodologies: A Review of the Waterfall Model and ObjectOriented Approach', *International Journal of Scientific & Engineering Research*, vol. 4, no. 7, pp. 427–434, 2013, issn: 2229-5518.
- [68] A. Alshamrani and A. Bahattab, 'A Comparison Between Three SDLC Models Waterfall Model, Spiral Model, and Incremental/Iterative Model', *International Journal of Computer Science Issues*, vol. 12, no. 1, pp. 106–111, 2015, issn: 1694-0784.
- [69] W. W. Royce, 'MANAGING THE DEVELOPMENT OF LARGE SOFTWARE SYSTEMS', in *Proceedings of the 9th International Conference on Software Engineering*, Mar. 1987, pp. 328–338.
- [70] D. Ibrahim, 'PIC32 Microcontrollers and the Digilent chipKIT', 1st ed., in *PIC32 Microcontrollers and the Digilent chipKIT*, Newnes, 2015, ch. 3, pp. 61–83, doi: 10.1016/B978-0-08-099934-0.00003-X.
- [71] ISO/IEC/IEEE International Standard - Software engineering - Software life cycle processes - Maintenance, in ISO/IEC/IEEE 14764:2022(E), pp.1-46, Jan. 2022, doi: 10.1109/IEEESTD.2022.9690131.
- [72] A. P. Stublen, C. M. Wellman, S. A. Kell, and T. W. Langston, 'Justifying and planning an energy monitoring system', *EEE Industry Applications Magazine*, vol. 3, no. 2, pp. 54–61, Mar. 1997, doi: 10.1109/2943.579137.
- [73] L. K. Thomas and W. A. Buan, 'Installation of a power monitoring system in a large, multiple power source, industrial facility', in *Proceedings of Conference Record of 1995 Annual Pulp and Paper Industry Technical Conference*, 1995, pp. 35–53, doi: 10.1109/PAPCON.1995.404853.

- [74] S. Taljaard, J. F. Van Rensburg, and H. J. Groenewald, 'Comparative study of mine dewatering control systems', in *Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, Aug. 2018, pp. 1–7, issn: 2166-059X.
- [75] A. Nell, 'Development of a dewatering control strategy to prevent flooding within deep-level mines', M.Eng. Dissertation, School of Mechanical Engineering, North-West University, Potchefstroom, South Africa, 2022.
- [76] J. R. van Gaasbeek and J. N. Martin, 'Getting to Requirements: The W5H Challenge', *INCOSE International Symposium*, vol. 11, no. 1, pp. 1083–1088, 2001, doi: 10.1002/J.2334-5837.2001.TB02413.X.
- [77] H. Mcheick, J. Sayegh, and H. Ajami, 'Context-Aware Healthcare Adaptation Model for COPD Diseases', in *Proceedings of International Conference on Smart Homes and Health Telematics*, Jun. 2020, pp. 307–315, doi: 10.1007/978-3-030-51517-1_27/FIGURES/2.
- [78] M. Sultan and A. V. Miranskyy, 'Ordering stakeholder viewpoint concerns for holistic and incremental Enterprise Architecture: the W6H framework', in *Proceedings of Symposium on Applied Computing*, Apr. 2018, pp. 78–85, doi: 10.1145/3167132.3167137.
- [79] B. W. Boehm, 'Verifying and Validating Software Requirements and Design Specifications', *IEEE Software*, vol. 1, no. 1, pp. 75–88, 1984, doi: 10.1109/MS.1984.233702.
- [80] ISO/IEC/IEEE International Standard - Systems and software engineering - Vocabulary, in *ISO/IEC/IEEE 24765:2010(E)*, 1st Ed., pp.1–418, Dec. 2010, doi: 10.1109/IEEESTD.2010.5733835.
- [81] NASA, 'Distinctions between Product Verification and Product Validation', in *NASA Systems Engineering Handbook*, 2nd ed., G. Shea, Ed., Washington, DC, 2016, p. 11. Accessed: Feb. 04, 2023. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2018/09/nasa_systems_engineering_handbook_0.pdf.
- [82] E. Vitz, J. W. Moore, J. Shorb, X. Prat-Resina, T. Tim Wendorff, and A. Hahn, 'Errors in Measurement', in *ChemPRIME*, University of Wisconsin, Madison: LibreTexts, 2023, p. 42.

- [83] U. Khair, H. Fahmi, S. Al Hakim, and R. Rahim, 'Forecasting Error Calculation with Mean Absolute Deviation and Mean Absolute Percentage Error', *Journal of Physics: Conference Series*, vol. 930, no. 1, pp. 1–6, Dec. 2017, doi: 10.1088/1742-6596/930/1/012002.
- [84] J. José, P. Pol, S. Abad, C. Blasco, J. Montañó, J. Moreno, A. P. Pol, A. S. Abad and B. C. Cajal, 'Using the R-MAPE index as a resistant measure of forecast accuracy', *Psicothema*, vol. 25, no. 4, pp. 500–506, 2013, doi: 10.7334/psicothema2013.23.
- [85] D. J. von Lehmden and C. Nelson, 'Data Review, Verification and Validation', in *Quality Assurance Handbook for Air Pollution Measurement Systems*, vol. 2, United States: Environmental Protection Agency, Research Triangle Park, N.C. (USA). Environmental Monitoring and Support Lab., 2017, pp. 1–7.
- [86] IEEE Standard for Software Maintenance, in IEEE Std 1219-1998, pp.1-56, Oct. 1998, doi: 10.1109/IEEESTD.1998.88278
- [87] S. Anwar, A. Adnan, M. M. Alam, and T. Ali, 'Architecture based software quality maintenance ripple effect analysis', *International journal of innovative computing, information and control (IJICIC)*, vol. 8, no. 1, pp. 489–500, 2012, issn: 1349-4198.
- [88] S. Bolognani, 'Methods and applications in networked control and Feedback control design for quantum systems', Ph.D. Thesis, School of Information Engineering University of Padova, Veneto, Italy, 2011.
- [89] R. Wolfson, 'Electricity', in *Energy, Environment, and Climate*, 2nd ed., New York: W.W. Norton & Company, 2012, pp. 292–307.
- [90] R. T. Paynter and B. J. T. Boydell, 'Power Transmission and Distribution: An Overview', in *Introduction to Electricity*, 1st ed., New Jersey: Pearson Upper Saddle River, 2011, pp. 1095–1097.
- [91] Eskom, '*Tariffs and Charges Booklet 2023/2024*', South Africa, 2023, Accessed: Sep. 9, 2023, [Online]. Available: https://www.eskom.co.za/distribution/wp-content/uploads/2023/08/2023_24-Tariff-Book_01042023-v6.pdf.
- [92] Eskom, '*Tariffs and Charges Booklet 2021/2022*', 2021. Accessed: Aug. 26, 2021. [Online]. Available: <https://www.eskom.co.za/distribution/wp-content/uploads/2022/04/Tariff-Booklet-final.pdf>.

APPENDIX A: ELECTRICAL GRID BACKGROUND

The electrical grid can be described as an intricate system which is designed to distribute electricity from its generation to customers for daily use. These systems have developed from small local designs to consisting of numerous complex interconnections which expand across thousands of kilometres. Figure 69 showcases a schematic of the electrical grid.

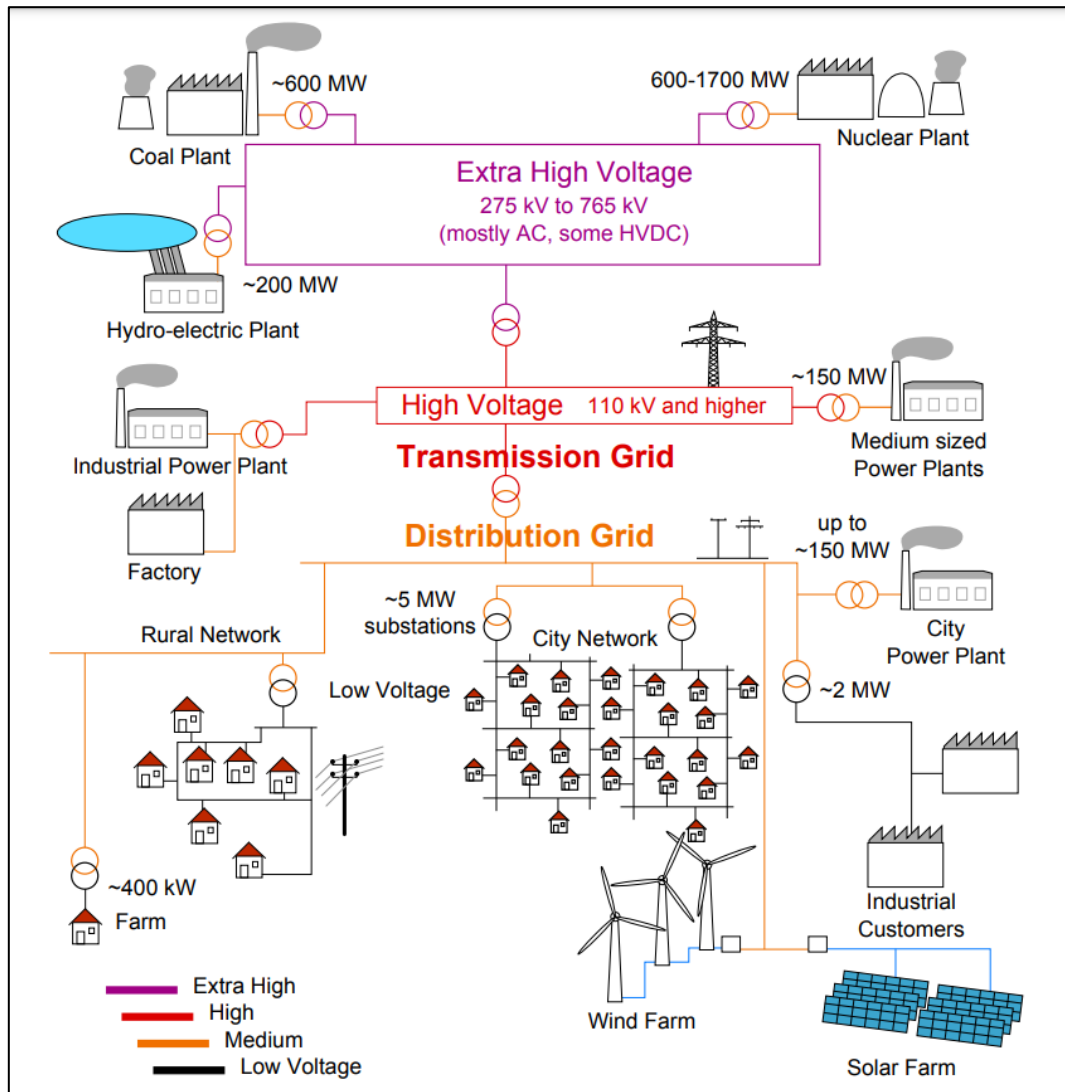


Figure 69: Schematic representation of the electrical grid [88]

The electrical grid can be summarised into three main sections, namely electricity generation, electrical transmission, and distribution⁷¹.

⁷¹ Energy Education, 'Electrical grid', 2022. https://energyeducation.ca/encyclopedia/Electrical_grid#cite_ref-wolf_1-1 (accessed Sep. 09, 2023).

Electricity generation starts at a power plant where the mechanical energy of a turbine is converted into electrical energy using a generator. Solar power generation is an exception, as it uses PV cells which converts the solar radiation from the sun into electricity [89]. Power plants utilise various energy sources, such as outlined in **Error! Reference source not found.**, to generate electricity. Figure 70 provides an example of a coal-fired power plant.



Figure 70: Coal-fired power plant⁷²

These power plants, such as the coal-fired power plant presented in Figure 70, are often located in remote areas far away from the demand for electricity. Electrical transmission is used to address this issue⁷³.

Electrical transmission is the process of distributing the generated electricity from the power plants to the distribution grid via high-voltage power lines, as depicted in Figure 71. The electricity from the power plant passes through a step-up substation where the voltage is increased via a transformer. This allows electricity to be transmitted sufficiently via the high-voltage power lines over long distances [90].

A step-down substation can then be used to lower the voltage of these high-voltage power lines to a sub-transmission voltage, which is occasionally used for industrial processes. Alternatively, the electricity is supplied to a distribution substation where the sub-transmission

⁷² Obtained from: Eskom, 'Coal fired power stations', 2021. <https://www.eskom.co.za/eskom-divisions/gx/coal-fired-power-stations/> (accessed Sep. 09, 2023).

⁷³ Energy Education, 'Electrical grid', 2022. https://energyeducation.ca/encyclopedia/Electrical_grid#cite_ref-wolf_1-1 (accessed Sep. 09, 2023).

voltage is further lowered via a step-down transformer where it forms part of the distribution grid^{74, 75}. Figure 72 provides an example of a distribution substation.



Figure 71: High-voltage power lines⁷⁶



Figure 72: Distribution substation⁷⁷

⁷⁴ Energy Education, 'Electrical grid', 2022. https://energyeducation.ca/encyclopedia/Electrical_grid#cite_ref-wolf_1-1 (accessed Sep. 09, 2023).

⁷⁵ Occupational Safety and Health Administration, 'eTool : Electric Power Generation, Transmission, and Distribution - Glossary of Terms', <https://www.osha.gov/etools/electric-power/glossary-terms#term-s> (accessed Sep. 09, 2023).

⁷⁶ Obtained from: K. Siwele, 'S. Africa Minister Says Power Cuts May End Sooner Than Expected', 2023. <https://www.bloomberg.com/news/articles/2023-07-09/s-africa-minister-says-power-cuts-may-end-sooner-than-expected#xj4y7vzkg> (accessed Sep. 09, 2023).

⁷⁷ Obtained from: Adenco Construction, 'Klipfontein Substation', 2015. <https://www.adenco.co.za/klipfontein-substation/> (accessed Sep. 09, 2023).

The distribution grid is the final stage of the electrical grid where the electricity is distributed to industrial, residential, or other consumers. Overhead and underground sub-transmission power lines connect to the distribution grid from where it is then distributed via lower-voltage power lines to consumers⁷⁸.

⁷⁸ Energy Education, 'Electrical grid', 2022. https://energyeducation.ca/encyclopedia/Electrical_grid#cite_ref-wolf_1-1 (accessed Sep. 09, 2023).

APPENDIX B: HIGH-LEVEL POD BREAKDOWN

This section provides a high-level overview of the POD split into the individual incomers as presented in Figure 73.

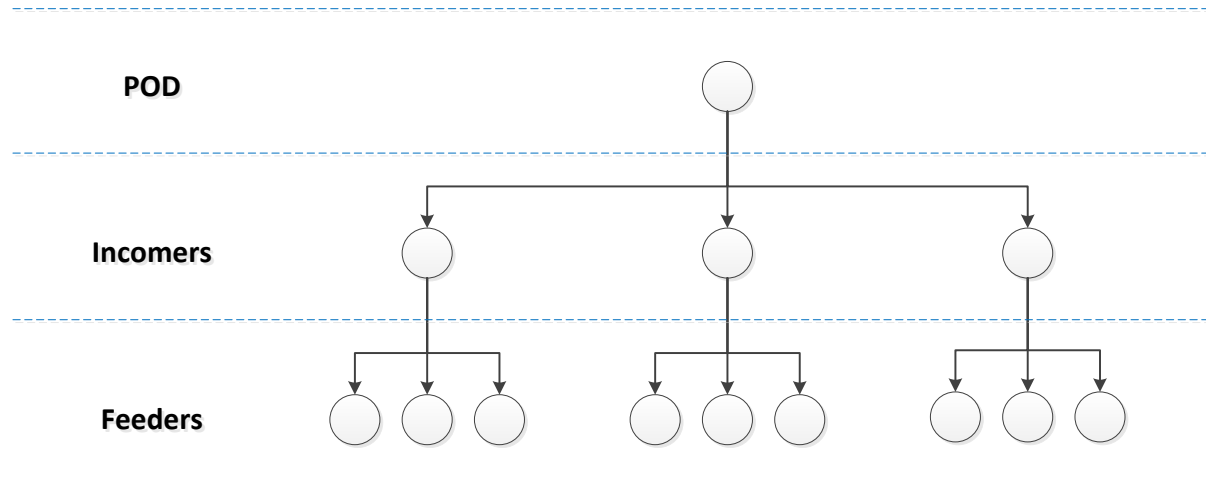


Figure 73: High-level POD split into incomers

The POD is typically split into the incomers which feed power into the substation. The electrical equipment is then supplied with power via the transmission lines (feeders) from the substation^{79, 80}.

The total power consumption at the POD is equivalent to the combined power consumption of the individual incomers. The individual incomers may prove to provide valuable insight with regards to the overall POD performance, as the performance of the incomers should be reflected on the POD.

⁷⁹ E. Fahad, 'Substation: Substation Configuration, Working, Busbar, and Earthing', 2020. <https://www.electronicclinic.com/substation-substation-configuration-working-busbar-and-earthing/> (accessed Sep. 08, 2023).

⁸⁰ Electrical 4U, 'Low Voltage Switchgear or LV Switchgear', 2020. <https://www.electrical4u.com/low-voltage-switchgear/> (accessed Sep. 08, 2023).

APPENDIX C: ESKOM TARIFFS AND DESCRIPTIONS

This section provides an overview of the Eskom tariff booklet pertaining to listed abbreviations, definitions, tariff structures, and descriptions. An example of an Eskom bill is presented in Figure 83.

ABBREVIATIONS			
<	less than	kW	kilowatt
≤	less than or equal to	kWh	kilowatt-hour
>	greater than	MEC	maximum export capacity
≥	greater than or equal to	MFMA	Municipal Finance Management Act
A	ampere	MV	medium voltage
c	cents	MVA	megavolt-ampere
c/kVAh	cents per reactive kilovolt-ampere-hour	MYPD	multi-year price determination
c/kWh	cents per kilowatt-hour	N/A	not applicable
CPI	consumer price index	NERSA	National energy regulator of South Africa
DUoS	Distribution use-of-system	NMD	notified maximum demand
ERS	electrification and rural subsidy	PF	power factor
ETUoS	embedded Transmission use-of-system	POD	Point of delivery
Gen	Generator	R	rand
GWh	gigawatt-hour	R/kVA	rand per kilovolt-ampere
HV	High Voltage	TOU	time of use or time-of-use
IPP	Independent Power Producer	TUoS	Transmission use-of-system
km	kilometre	UoS	Use-of-system
kVA	kilovolt-ampere	V	volt
kVAh	reactive kilovolt-ampere-hour	VAT	value-added tax
kV	kilovolt	W	watt

Figure 74: Eskom tariff booklet listed abbreviations [91]

DEFINITIONS

Account means the invoice received by a customer for a single **POD/point of supply** or if consolidated, multiple **points of delivery/supply** for electricity supplied and/or use of the **System**.

Active energy charge or energy charge means the charge for each unit of energy consumed, typically charged for as c/kWh.

Administration charge means the daily fixed charge payable per **POD/point of supply/service agreement** to recover administration-related costs such as meter reading, billing, and meter capital. It is based on the **monthly utilised capacity** or **monthly maximum exported capacity** per **POD/point of supply/service agreement**.

Affordability subsidy charge means the transparent charge indicating socio-economic subsidies related to the supply of electricity to **residential tariffs** and is payable on Eskom related active energy sales to **non-local authority tariffs**.

Ancillary Service charge means the charge that recovers the cost of providing ancillary services by the System Operator.

Annual utilised capacity means the higher of the **notified maximum demand (NMD)** or the **maximum demand**, per **POD/point of supply** measured in kVA, and registered during a rolling 12-month period.

Annual maximum export capacity means the higher of the notified **maximum export capacity (MEC)** or the actual **maximum exported capacity**, per **point of supply** measured in kW, and registered during a rolling 12-month period.

Chargeable demand means the highest average demand measured in kVA in a billing month during the chargeable time periods specified for each tariff. For WEPS, Megaflex and Megaflex Gen, the chargeable period is during these tariffs peak and standard periods and for Nightsave Urban (Large and Small) and Nightsave Rural during Nightsave's peak periods.

Code means the Distribution Code, the South African Grid Code, the Grid Connection Code for Renewable Power Plants, or any other code, published by NERSA, as applicable, and as amended, modified, extended, replaced or re-enacted from time to time.

Distribution means the regulated business unit through which Eskom constructs, owns, operates, and maintains the **Distribution System** in accordance with its licence and the **Code**.

Distribution connected means connected to the **Distribution system**.

Distribution losses charge means the production-based (energy) charge to generators. The losses charge is based on the approved loss factors, the load factor, the amount of energy produced seasonally and TOU and the WEPS energy rate (excluding losses).

Figure 75: Eskom tariff booklet listed definitions – section 1 [91]

Distribution network capacity charge (previously known as the **Distribution network access charge**) means the R/kVA or R/POD fixed network charge raised to recover **Distribution** network costs and depending on the tariff is charged on the **annual utilised capacity** or **maximum export capacity** where **maximum demand** is measured or the **NMD** where **maximum demand** is not measured.

Distribution network demand charge means the R/kVA or c/kWh variable network charge raised to recover **Distribution** network costs and depending on the tariff may be charged on the **chargeable demand** or the active energy.

Distribution System means Eskom's network infrastructure consisting of assets operated at a nominal voltage of 132 kV or less, not classified as transmission transformation equipment.

Distribution use-of-system (DUoS) charges means the network tariffs charged for making capacity available, connecting to and for the use of the **Distribution System**. The **DUoS** charges are the source of the **Distribution** network charge components in the retail tariff structures.

DUoS charge (generators) means the **DUoS** charges payable by generators. These **DUoS** charges for generators comprise the **network capacity charge** based on **maximum export capacity**, the **losses charge**, the **ancillary service charge**, the **service charge** and the **administration charge**.

DUoS charge (loads) means the **DUoS** charges payable by loads. These **DUoS** charges comprise the **network capacity charge**, the **network demand charge**, the **urban low voltage subsidy charge**, the **ancillary service charge**, the **service charge**, the **administration charge** and the **electrification and rural network subsidy charge**.

Electrification and rural network subsidy charge means the **DUoS charge** transparently indicating the contribution towards socio-economic network-related subsidies for Residential and **Rural_p** tariffs and is payable by loads that use the **Distribution** or **Transmission System** for the delivery of energy.

Energy demand charge means the seasonally differentiated charge per **POD** that recovers peak energy costs and is based on the **chargeable demand**.

Embedded Transmission use-of-system (ETUoS) charge means the **TUoS** charges payable by customers connected to the **Distribution** network.

Excess network capacity charge (previously known as the **excess network access charge**) means the charge payable with reference to the **NMD rules** and is based on the maximum demand exceeding the **NMD** multiplied by the **event number** (recorded every time the **NMD** is exceeded) multiplied by the applicable **network capacity charges** for the tariff.

High-demand season means the **TOU** Period from 1 June to 31 August of each year.

High voltage (HV) networks usually consist of equipment supplied at a voltage greater than 22 kV and consist of the distribution substations and networks. A substation is considered an **HV** substation when the primary side of the substation is supplied at a voltage > 22 kV.

Key customer means a customer that consumes more than 100 GWh per annum on a contiguous site under a single management structure or is prepared to pay to be a Key Customer.

Local authority tariffs mean tariffs applicable to municipal bulk points of supply.

Loss factors mean the factor indicating the cost or benefit of technical energy losses on the **Transmission** and the **Distribution System**. The **Distribution loss factors** differ per voltage category and per **Rural_p** and **Urban_p** categories. The **Transmission loss factors** differ for generators and loads and are based on the **Transmission zones**.

Losses charge means the charge payable based on the applicable **loss factors** and the **WEPS** rate excluding losses.

Low-demand season means the **TOU** Period from 1 September to 31 May of each year.

Maximum demand/exported capacity means the highest average demand measured in kVA or kW at the **POD/point of supply** during a 30-minute integrating period in a billing month.

Maximum export capacity (MEC) means the maximum capacity at the **point(s) of supply** notified by the customer and accepted by Eskom for the transmission of electrical energy between a generator and the **Transmission or Distribution System**. *Note: The notification of the maximum export capacity shall be governed by the **NMD** and **MEC** rules.*

Medium voltage (MV) networks consist of the networks above 1 kV up to 22 kV. Eskom has specifically designated some rural networks with a voltage of 33 kV as rural reticulation networks. A substation is considered a **MV** substation when the primary side of the substation is supplied at a voltage ≤ 22 kV.

Monthly maximum exported capacity means the higher of the notified **maximum export capacity (MEC)** or the actual **maximum exported capacity**, measured in kW registered during the billing month.

Monthly utilised capacity means the higher of the notified **maximum demand (NMD)** or the **maximum demand**, measured in kVA or kW registered during the billing month.

Network capacity charge (previously known as the **network access charge**) means the R/kVA or R/POD fixed network charge raised to recover network costs and depending on the tariff is charged on the **annual utilised capacity** or **maximum export capacity** where **maximum demand** is measured or the **NMD** where **maximum demand** is not measured.

Network demand charge means the R/kVA or c/kWh variable network charge raised to recover network costs and depending on the tariff may be charged on the **chargeable demand** or the active energy.

Non-local authority tariffs mean the tariffs applicable to Eskom's direct customers (i.e., customers within Eskom's licensed area of supply) and exclude the **non-local authority tariffs**.

Notified maximum demand (NMD) means the contracted **maximum demand**, notified in writing by the customer and accepted by Eskom per **POD/point of supply**. *Note: The notification of demand shall be governed by the **NMD** (and **MEC**) rules.*

Figure 76: Eskom tariff booklet listed definitions – section 2 [91]

NMD (and MEC) rules means the rules approved by NERSA and as amended from time to time for the notification of demand or maximum export capacity or changes to or exceedances of the **NMD or MEC**.

Off-peak period means the **TOU periods** of relatively low **system** demand.

Peak period means the **TOU periods** of relatively high system demand.

Point of delivery (POD)/point of supply means either a single point of supply, or a specific group of points of supply on Eskom's **System**, from where electricity is supplied to the customer by Eskom, or from where the customer supplies electricity to Eskom's **System** located within a single substation, at which electricity is supplied/delivered to the customer at the same declared voltage and tariff. Note: This can be a metering or summation point.

Public holidays mean the treatment of charges on **public holidays** as specified by Eskom.

Reactive energy charge means a c/kVAh charge based on the power factor and tariff of the **POD**.

Residential tariffs mean the Homelight and Homepower suite of tariffs.

Rural_p means areas classified as rural by Eskom for the purposes of tariff design and classification.

Service agreement means each tariff /transaction/contract linked to an account.

Service and administration charge means the monthly charge payable per **account/service agreement** for service and administration related costs. (Also see **service charge** and **administration charge**).

Service charge means the daily fixed charge payable per **account** to recover service-related costs and is based on the sum of the **monthly utilised capacity(s)** or **maximum export capacity(s)** of all **PODs** linked to an **account**.

Standard period means the **TOU periods** of relatively mid system demand.

Standard charge/fee means the fees/charges described in the paragraph below.

System means the **Transmission** and **Distribution** network infrastructure consisting of all lines and substation equipment.

Time-of-use (TOU) tariff means a tariff with energy charges that change during different **TOU periods** and seasons.

TOU periods mean time blocks based on the volume of electricity demand during high, mid and low demand periods and may differ per tariff. The **TOU periods** typically are **peak**, **standard**, and **off-peak** periods and differ during in **high** and **low demand seasons**.

Transmission means the regulated business unit through which Eskom constructs, owns, operates and maintains the **Transmission System** in accordance with its licence and the **Code**.

Transmission connected means connected to the **Transmission system**.

Transmission system means Eskom's electricity **system** consisting of all lines and substation equipment where the nominal voltage is above 132 kV or where the nominal voltage is lower than or equal to 132 kV and there are no **Distribution System** assets.

Transmission use-of-system (TUoS) charges means the network tariffs charged for making capacity available, connecting to and for the use of the **Transmission System**. The **TUoS** charges are the source of the **ETUoS** and the **Transmission network charge** components in the retail tariff structures.

Transmission network access charge means the same as **Transmission network charge**.

Transmission network charge means the network related **TUoS** charge.

Transmission zone(s) means the geographic differentiation, applicable to **Transmission** network charges and **loss factors**, to indicate the costs associated with the delivery and transmission of energy.

Urban_p areas means areas classified by Eskom as urban for the purposes of tariff design and classification.

Urban low voltage subsidy charge means the charge transparently indicating the network-related cross subsidy payable by ≥ 66 kV **Urban_p** connected supplies for the benefit of < 66 kV connected **Urban_p** supplies.

Utilised capacity means the same as **annual utilised capacity**.

STANDARD FEES/CHARGES FOR SERVICES RENDERED

In addition to the standard tariff charges set out in this schedule, Eskom may raise additional standard fees/charges for direct services rendered to a customer s e.g. the provision of service mains, the installation of equipment in the customer's substation, for the taking of any special meter readings, for reconnection of the supply after disconnection (i) either at the request of the customer or (ii) caused by the customer in failure to carry out its obligations, and for special/additional work done for the customer by Eskom. Refer to www.eskom.co.za/tariffs for the list of standard/charges/fees applicable.

Figure 77: Eskom tariff booklet listed definitions – section 3 [91]

MEGA FLEX

TOU electricity tariff for Urban_p customers with an NMD greater than 1 MVA with the following charges:

- seasonally and **time-of-use** differentiated c/kWh **active energy charges** including losses, based on the voltage of supply and the **Transmission zone**;
- three **time-of-use** periods namely **peak**, **standard** and **off-peak**, as specified in *Appendix A - Eskom's Defined Time-Of-Use Periods*;
- the treatment of **public holidays** for the raising of the **active energy charge** and the **network demand** charge shall be as specified in *Appendix D - Treatment Of Public Holidays For 2022/23*;
- a R/kVA/month **Transmission network charge** based on the voltage of the supply, the **Transmission zone** and the **annual utilised capacity** measured at the **POD** applicable during all time periods;
- a R/kVA/month **Distribution network capacity charge** based on the voltage of the supply and the **annual utilised capacity** measured at the **POD** applicable during all time periods;
- a R/kVA/month **Distribution network demand charge** based on the voltage of the supply and the **chargeable demand** measured at the **POD** applicable during **peak** and **standard** periods;
- a R/kVA **urban low voltage subsidy charge** based on the voltage of the supply and charged on the **annual utilised capacity** measured at the **POD** applicable during all time periods
- a c/kWh **ancillary service charge** based on the voltage of the supply applicable during all time periods;
- a R/account/day **service charge** based on the **monthly utilised capacity** of each **account**;
- a R/POD/day **administration charge** based on the **monthly utilised capacity** of each **POD** linked to an **account**;
- a c/kVArh **reactive energy charge** supplied in excess of 30% (0,96 power factor or less) of the kWh recorded during the **peak** and **standard** periods. The excess reactive energy is determined per 30-minute integrating period and accumulated for the month and will only be applicable during the **high-demand season**;
- a c/kWh **electrification and rural network subsidy charge**, applied to the total active energy measured at the **POD** in the month;
- a c/kWh **affordability subsidy charge** applied to the total active energy purchased from Eskom at the **POD** in the month – applicable to **non-local authority** tariffs only; and
- an **excess network capacity charge** shall be payable in the event of an **NMD** exceedance as specified in an in accordance with the **NMD rules** and as set out in *Appendix C - NMD Rules for the relevant tariff*.

Figure 78: Eskom tariff booklet Mega Flex charges descriptions [20]

MEGA FLEX

Non - Local Authority charges

Nightsave Urban Small - 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 VAT incl	Standard VAT incl	Off Peak VAT incl	Peak VAT incl	Standard VAT incl	Off Peak VAT incl	VAT incl
≤ 300km	< 500V	417.36	479.96	126.98	146.03	69.34	79.74	136.67
	≥ 500V & < 66kV	410.81	472.43	124.45	143.12	67.59	77.73	133.99
	≥ 66kV & ≤ 132kV	397.80	457.47	120.50	138.58	65.45	75.27	129.78
	> 132kV*	374.91	431.15	113.56	130.59	61.68	70.93	122.33
> 300km and ≤ 600km	< 500V	420.76	483.87	127.49	146.61	69.22	79.60	137.27
	≥ 500V & < 66kV	414.91	477.15	125.68	144.53	68.25	78.49	135.37
	≥ 66kV & ≤ 132kV	401.71	461.97	121.68	139.93	66.06	75.97	131.03
	> 132kV*	378.67	435.47	114.73	131.94	62.26	71.60	123.51
> 600km and ≤ 900km	< 500V	424.95	488.69	128.73	148.04	69.88	80.36	138.62
	≥ 500V & < 66kV	419.08	481.94	126.97	146.02	68.94	79.28	136.70
	≥ 66kV & ≤ 132kV	405.81	466.68	122.94	141.38	66.75	76.76	132.37
	> 132kV*	382.48	439.85	115.85	133.23	62.95	72.39	124.76
> 900km	< 500V	429.23	493.61	130.08	149.59	70.60	81.19	140.03
	≥ 500V & < 66kV	423.25	486.74	128.20	147.43	69.59	80.03	138.04
	≥ 66kV & ≤ 132kV	409.88	471.36	124.15	142.77	67.41	77.52	133.69
	> 132kV*	386.21	444.14	117.04	134.60	63.59	73.13	126.06

*132 kV or Transmission connected

Distribution network charges

Voltage	Network capacity charge (R/kVA/m)	Network demand charge (R/kVA/m)	Urban low voltage subsidy charge (R/kVA/m)
< 500V	R 23.73	R 27.29	R 44.99
≥ 500V & < 66kV	R 21.76	R 25.02	R 41.27
≥ 66kV & ≤ 132kV	R 7.77	R 8.94	R 14.39
> 132kV/ Transmission connected	R 0.00	R 0.00	R 0.00

Ancillary service charge (c/kWh)

Voltage	Ancillary service charge (c/kWh)
< 500V	0.55
≥ 500V & < 66kV	0.54
≥ 66kV & ≤ 132kV	0.52
> 132kV *	0.48

*132 kV or Transmission connected

Reactive energy charge [c/kVAh]

High season	Low season
19.19	22.01

Electrification and rural network subsidy charge

10.61	12.20
-------	-------

Affordability subsidy charge (c/kWh)

4.98	5.73
------	------

Customer categories

> 1 MVA	R 272.39	R 313.25
Key customers	R 5 337.86	R 6 138.54

Service charge (R/account/day)

R 272.39	R 313.25
R 5 337.86	R 6 138.54

Administration charge (R/POD/day)

R 122.76	R 141.17
R 170.47	R 196.04

Figure 79: 2021/2022 Eskom Mega Flex non-local authority charges [92]

MEGA FLEX

Non - Local Authority charges

Megaflex - 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 VAT incl	Standard VAT incl	Off Peak VAT incl	Peak VAT incl	Standard VAT incl	Off Peak VAT incl	Peak VAT incl	Standard VAT incl	Off Peak VAT incl					
≤ 300km	< 500V	457,47	526,09	139,18	160,06	76,00	87,40	149,80	172,27	103,36	118,86	65,90	75,79	R 13,09	R 15,05
	≥ 500V & < 66kV	450,29	517,83	136,41	156,87	74,09	85,20	146,87	168,90	101,10	116,27	64,14	73,76	R 11,96	R 13,75
	≥ 66kV & ≤ 132kV	436,03	501,43	132,08	151,89	71,74	82,50	142,25	163,59	97,88	112,56	62,13	71,45	R 11,64	R 13,39
	> 132kV*	410,94	472,58	124,47	143,14	67,61	77,75	134,09	154,20	92,26	106,10	58,54	67,32	R 14,72	R 16,93
> 300km and ≤ 600km	< 500V	461,20	530,38	139,74	160,70	75,87	87,25	150,46	173,03	103,59	119,13	65,72	75,58	R 13,18	R 15,16
	≥ 500V & < 66kV	454,78	523,00	137,76	158,42	74,81	86,03	148,38	170,64	102,10	117,42	64,77	74,49	R 12,07	R 13,88
	≥ 66kV & ≤ 132kV	440,31	506,36	133,37	153,38	72,41	83,27	143,62	165,16	98,85	113,68	62,72	72,13	R 11,73	R 13,49
	> 132kV*	415,06	477,32	125,76	144,62	68,24	78,48	135,38	155,69	93,16	107,13	59,09	67,95	R 14,85	R 17,08
> 600km and ≤ 900km	< 500V	465,79	535,66	141,10	162,27	76,60	88,09	151,94	174,73	104,59	120,28	66,33	76,28	R 13,33	R 15,33
	≥ 500V & < 66kV	459,35	528,25	139,17	160,05	75,57	86,91	149,84	172,32	103,14	118,61	65,43	75,24	R 12,18	R 14,01
	≥ 66kV & ≤ 132kV	444,81	511,53	134,75	154,96	73,16	84,13	145,09	166,85	99,88	114,86	63,37	72,88	R 11,80	R 13,57
	> 132kV*	419,24	482,13	126,98	146,03	69,00	79,35	136,75	157,26	94,11	108,23	59,72	68,68	R 15,07	R 17,33
> 900km	< 500V	470,48	541,05	142,58	163,97	77,38	88,99	153,49	176,51	105,62	121,46	67,03	77,08	R 13,42	R 15,43
	≥ 500V & < 66kV	463,92	533,51	140,52	161,60	76,28	87,72	151,31	174,01	104,12	119,74	66,07	75,98	R 12,32	R 14,17
	≥ 66kV & ≤ 132kV	449,27	516,66	136,08	156,49	73,89	84,97	146,54	168,52	100,86	115,99	63,99	73,59	R 11,91	R 13,70
	> 132kV*	423,32	486,82	128,29	147,53	69,70	80,16	138,17	158,90	95,14	109,41	60,38	69,44	R 15,18	R 17,46

*132 kV or Transmission connected

Distribution network charges

Voltage	Network capacity charge (R/kVA/m)	Network demand charge (R/kVA/m)	Urban low voltage subsidy charge (R/kVA/m)	
	VAT incl	VAT incl	VAT incl	VAT incl
< 500V	R 26,01	R 29,91	R 49,31	R 56,71
≥ 500V & < 66kV	R 23,85	R 27,43	R 45,24	R 52,03
≥ 66kV & ≤ 132kV	R 8,52	R 9,80	R 15,77	R 18,14
> 132kV/ Transmission connected	R 0,00	R 0,00	R 0,00	R 0,00
			R 21,01	R 24,16

Ancillary service charge (c/kWh)

Voltage	VAT incl
< 500V	0,60
≥ 500V & < 66kV	0,59
≥ 66kV & ≤ 132kV	0,57
> 132kV *	0,53

*132 kV or Transmission connected

Reactive energy charge [c/kVAh]

High season	Low season
VAT incl	VAT incl
21,03	24,18
0,00	0,00

Electrification and rural network subsidy charge

VAT incl
11,63

Affordability subsidy charge (c/kWh)

Only payable by non-local authority tariffs

VAT incl
5,69

Customer categories

Service charge (R/account/day)	Administration charge (R/POD/day)
VAT incl	VAT incl
> 1 MVA	R 298,57
Key customers	R 5 850,83
	R 134,56
	R 186,85
	R 154,74
	R 214,88

Figure 80: 2022/2023 Eskom Mega Flex non-local authority charges [20]

Appendix C - NMD Rules and Excess Network Capacity Charges

The NMD (and MEC rules)¹, as amended from time to time with the approval of NERSA, set out the rules relating to an notification, changes and exceedance of the **NMD and MEC**. For the rules please go to www.eskom.co.za/tariffs.

Charges applicable for exceedance of the NMD

An exceedance of the **NMD** based on the difference between the **maximum demand** and the NMD, will impact the following charges (as applicable); the **Distribution network capacity charge**², the **network capacity charge**^{*}, the **Transmission network charge** and the **urban low voltage subsidy charge** for the DUoS charges, the TUoS charges and the Ruraflex, Ruraflex Gen, Nightsave Rural, Megaflex, Megaflex Gen, Miniflex, Nightsave Urban Small and Nightsave Urban Large tariffs.

The amount payable through the **excess network capacity charge**² in the event of an exceedance is calculated on the number of times the **NMD** is exceeded by the **maximum demand** multiplied by the portion of the maximum demand exceeding the **NMD** multiplied by the sum of the **Distribution network capacity charge**² and the **Transmission network charge** (or for Miniflex and Ruraflex the **network capacity charge**²) and if applicable, the **urban low voltage subsidy charge** for the respective tariffs. The **excess network capacity charges** are set out below.

Charges applicable for exceedance of the MEC rules¹

These rules are in the process of being revised by NERSA. Please refer to the Eskom website (www.eskom.co.za/tariffs) for the latest version of the rules.

The charges below shall apply in the event of an NMD exceedance x the event number

1. Eskom submitted to Nersa an amendment to the NMD rules to include the MEC rules. Once this is decided on by NERSA, any rules associated with the MEC will apply.
2. Note that any reference in the NMD rules to “the network access charge” must be replaced with “the network capacity charge” and to “the excess network access charge” must be replaced with “excess network capacity charge”.

Figure 81: Eskom tariff booklet NMD rules [24]

Excess network capacity charges - Non-local authority

Urban - Excess NCC Megaflex/Megaflex Gen [non local authorities]				Urban - Excess NCC Nightsave Urban Large [non local authorities]				Urban Excess NCC Miniflex [non local authorities]			
		Excess NCC [R/kVA/m]				Excess NCC [R/kVA/m]				Excess NCC [R/kVA/m]	
Transmission Zone	Voltage	VAT incl		Transmission Zone	Voltage	VAT incl		Transmission Zone	Voltage	VAT incl	
≤ 300km	< 500V	R 39,10	R 44,97	≤ 300km	< 500V	R 39,10	R 44,97	≤ 300km	< 500V	R 39,04	R 44,90
	≥ 500V & < 66kV	R 35,81	R 41,18		≥ 500V & < 66kV	R 35,81	R 41,18		≥ 500V & < 66kV	R 35,79	R 41,16
	≥ 66kV & ≤ 132kV	R 41,17	R 47,35		≥ 66kV & ≤ 132kV	R 41,17	R 47,35		≥ 66kV & ≤ 132kV	R 41,11	R 47,28
	> 132kV*	R 35,73	R 41,09		> 132kV*	R 35,73	R 41,09		> 132kV*	R 35,66	R 41,01
> 300km and ≤ 600km	< 500V	R 39,19	R 45,07	> 300km and ≤ 600km	< 500V	R 39,19	R 45,07	> 300km and ≤ 600km	< 500V	R 39,14	R 45,01
	≥ 500V & < 66kV	R 35,92	R 41,31		≥ 500V & < 66kV	R 35,92	R 41,31		≥ 500V & < 66kV	R 35,90	R 41,29
	≥ 66kV & ≤ 132kV	R 41,26	R 47,45		≥ 66kV & ≤ 132kV	R 41,26	R 47,45		≥ 66kV & ≤ 132kV	R 41,19	R 47,37
	> 132kV*	R 35,86	R 41,24		> 132kV*	R 35,86	R 41,24		> 132kV*	R 35,82	R 41,19
> 600km and ≤ 900km	< 500V	R 39,34	R 45,24	> 600km and ≤ 900km	< 500V	R 39,34	R 45,24	> 600km and ≤ 900km	< 500V	R 39,33	R 45,23
	≥ 500V & < 66kV	R 36,03	R 41,43		≥ 500V & < 66kV	R 36,03	R 41,43		≥ 500V & < 66kV	R 36,01	R 41,41
	≥ 66kV & ≤ 132kV	R 41,33	R 47,53		≥ 66kV & ≤ 132kV	R 41,33	R 47,53		≥ 66kV & ≤ 132kV	R 41,31	R 47,51
	> 132kV*	R 36,08	R 41,49		> 132kV*	R 36,08	R 41,49		> 132kV*	R 36,03	R 41,43
> 900km	< 500V	R 39,43	R 45,34	> 900km	< 500V	R 39,43	R 45,34	> 900km	< 500V	R 39,36	R 45,26
	≥ 500V & < 66kV	R 36,17	R 41,60		≥ 500V & < 66kV	R 36,17	R 41,60		≥ 500V & < 66kV	R 36,13	R 41,55
	≥ 66kV & ≤ 132kV	R 41,44	R 47,66		≥ 66kV & ≤ 132kV	R 41,44	R 47,66		≥ 66kV & ≤ 132kV	R 41,39	R 47,60
	> 132kV*	R 36,19	R 41,62		> 132kV*	R 36,19	R 41,62		> 132kV*	R 36,14	R 41,56
*132 kV or Transmission connected				*132 kV or Transmission connected				*132 kV or Transmission connected			

Urban - Excess NCC Nightsave Urban Small [non local authorities]				Rural - Excess NCC Nightsave Rural [non local authorities]				Rural - Excess NCC Ruraflex/Ruraflex Gen [non local authorities]			
		Excess NCC [R/kVA/m]				Excess NCC [R/kVA/m]				Excess NCC [R/kVA/m]	
Transmission Zone	Voltage	VAT incl		Transmission Zone	Voltage	VAT incl		Transmission Zone	Voltage	VAT incl	
≤ 300km	< 500V	R 39,10	R 44,97	≤ 300km	< 500V	R 19,58	R 22,52	≤ 300km	< 500V	R 27,36	R 31,46
	≥ 500V & < 66kV	R 35,81	R 41,18		≥ 500V & ≤ 22kV	R 17,99	R 20,69		≥ 500V & ≤ 22kV	R 25,07	R 28,83
	≥ 66kV & ≤ 132kV	R 41,17	R 47,35								
	> 132kV*	R 35,73	R 41,09								
> 300km and ≤ 600km	< 500V	R 39,19	R 45,07	> 300km and ≤ 600km	< 500V	R 19,61	R 22,55	> 300km and ≤ 600km	< 500V	R 27,44	R 31,56
	≥ 500V & < 66kV	R 35,92	R 41,31		≥ 500V & ≤ 22kV	R 18,05	R 20,76		≥ 500V & ≤ 22kV	R 25,22	R 29,00
	≥ 66kV & ≤ 132kV	R 41,26	R 47,45								
	> 132kV*	R 35,86	R 41,24								
> 600km and ≤ 900km	< 500V	R 39,34	R 45,24	> 600km and ≤ 900km	< 500V	R 19,80	R 22,77	> 600km and ≤ 900km	< 500V	R 27,58	R 31,72
	≥ 500V & < 66kV	R 36,03	R 41,43		≥ 500V & ≤ 22kV	R 18,17	R 20,90		≥ 500V & ≤ 22kV	R 25,34	R 29,14
	≥ 66kV & ≤ 132kV	R 41,33	R 47,53								
	> 132kV*	R 36,08	R 41,49								
> 900km	< 500V	R 39,43	R 45,34	> 900km	< 500V	R 19,85	R 22,83	> 900km	< 500V	R 27,70	R 31,86
	≥ 500V & < 66kV	R 36,17	R 41,60		≥ 500V & ≤ 22kV	R 18,21	R 20,94		≥ 500V & ≤ 22kV	R 25,35	R 29,15
	≥ 66kV & ≤ 132kV	R 41,44	R 47,66								
	> 132kV*	R 36,19	R 41,62								
*132 kV or Transmission connected											

Figure 82: 2022/2023 Eskom excess network capacity charges [24]

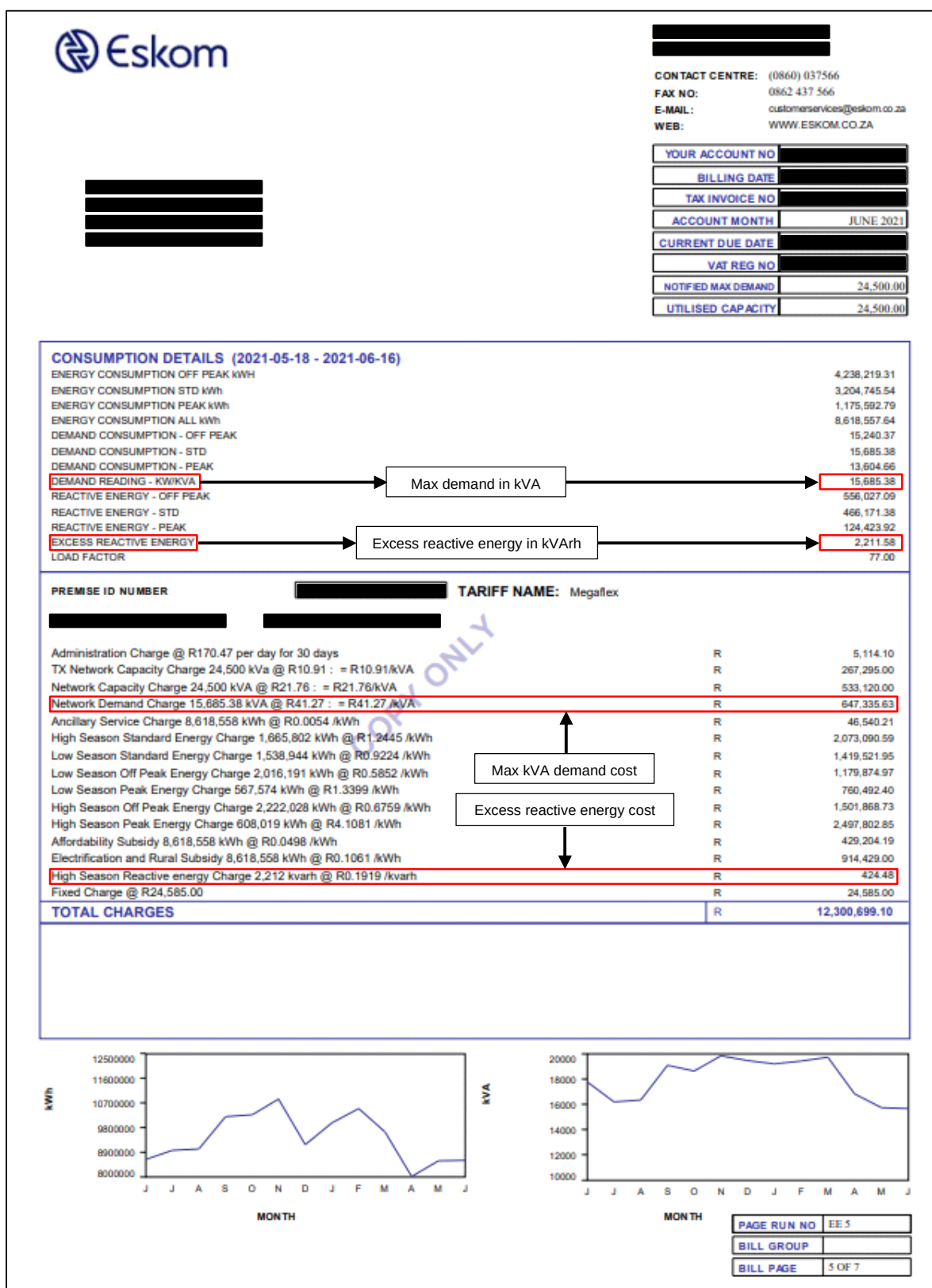


Figure 83: Eskom electricity bill example

APPENDIX D: POWER FACTORS IN INDUSTRY

Motor Load Factor	Power Factor
Unloaded	17%
$\frac{1}{4}$ Loaded	55%
$\frac{1}{2}$ Loaded	73%
$\frac{3}{4}$ Loaded	80%
Fully Loaded	84%
Overloaded (25%)	86%

Figure 84: Typical induction motor load factor versus power factor performance [25]

Typical Un-improved Power Factor by Equipment	
Equipment	Power Factor
Air Compressor & Pumps (external Motors)	75-80
Hermetic Motors (compressors)	50-80
Arc Welding	35-60
Resistance Welding	40-60
Machining	40-65
Arc Furnaces	75-90
Induction Furnaces (60Hz)	100
Standard Stamping	60-70
High Speed Stamping	45-60
Spraying	60-65

Figure 85: Typical power factor performance of industrial equipment [25]

APPENDIX E: BASIC SCADA EXAMPLE

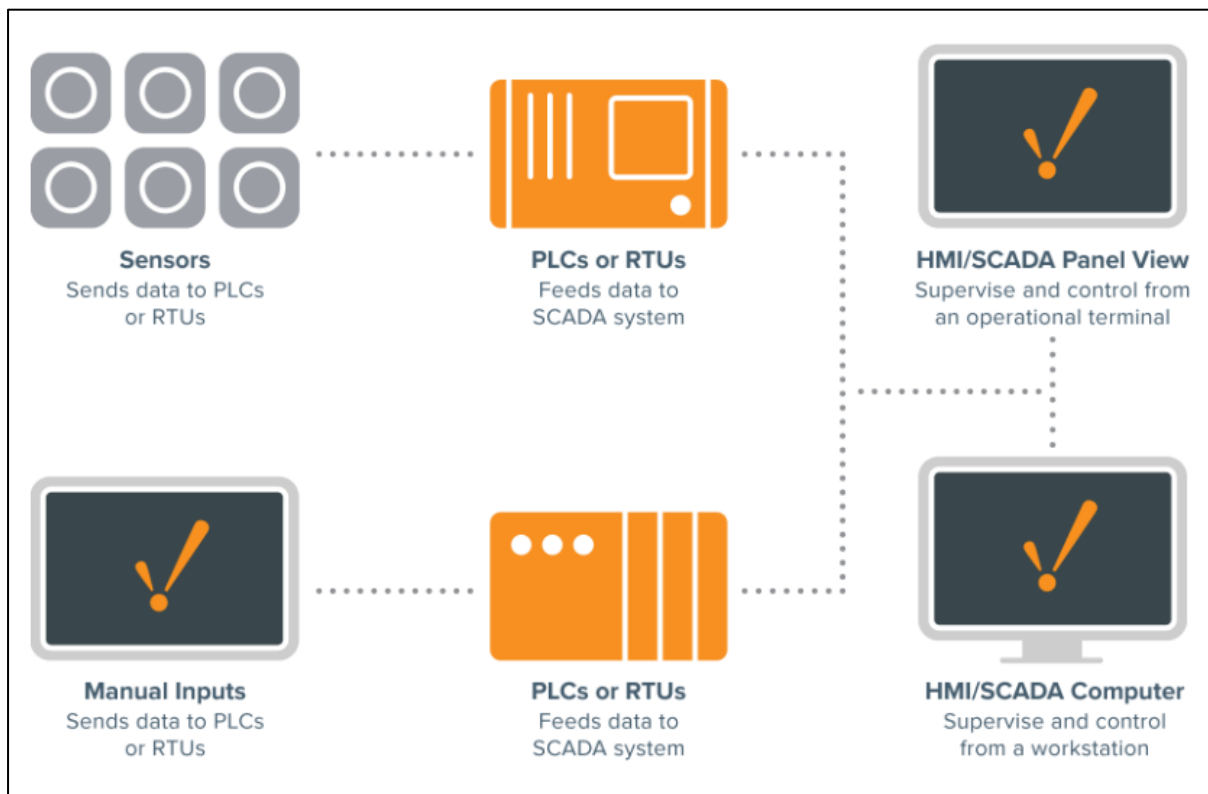


Figure 86: Overview of a basic SCADA system⁸¹

Figure 86 provides a high-level overview of the various components involved in a typical SCADA system. Manual and automatic inputs from connected equipment can be logged and stored on the system and accessed by a computer interface, as seen above. There are also control options available to communicate to instrumentation via the PLC to perform manual or automatic control.

⁸¹ Obtained from: Inductive Automation, 'What is SCADA? Supervisory Control and Data Acquisition', 2018. <https://inductiveautomation.com/resources/article/what-is-scada> (accessed Dec. 13, 2022).

APPENDIX F: REQUIREMENTS GATHERING AND STUDY TEMPLATES

This section provides the templates that were used to conduct the requirements gathering and analysis stage of the SDLC as shown in Section 3.2.3.

Table 34: Requirements gathering through 5W questions template

5W Questions and Answers	
Who?	
Question(s)	
Answer(s)	
What?	
Question(s)	
Answer(s)	
When?	
Question(s)	
Answer(s)	
Where?	
Question(s)	
Answer(s)	
Why?	
Question(s)	
Answer(s)	

Table 35: List of requirements template

List of Requirements	
5W	Requirements
Who	
What	
When	
Where	
Why	

Table 36: Requirements analysis template

Requirements Analysis	
Requirements	Analysis (H – How?)

Table 37: List of tools and features template

List of Tools and Features	
Tools	Features

APPENDIX G: BUSINESS INTELLIGENCE SOFTWARE

There are several free Business Intelligence (BI) software available that can be utilised to fulfil needs such as data analytics, monitoring, and reporting. Table 38 outlines some of the free BI tools available that can assist in providing valuable insight.

Table 38: Free Business Intelligence (BI) software options⁸²

Free Business Intelligence (BI) Software Options	
BI Software	Website Address
BIRT	https://eclipse.github.io/birt-website/
Microsoft Power BI	https://powerbi.microsoft.com/en-us/
Tableau Public	https://www.tableau.com/products/public
Heap Analytics	https://www.heap.io/pricing
Visualize Free	https://www.visualizefree.com/
Pentaho Community Edition	https://www.hitachivantara.com/en-us/products/dataops-software/data-integration-analytics/pentaho-community-edition.html
Zoho Analytics	https://www.zoho.com/analytics/
QlikView Personal Edition	https://help.qlik.com/en-US/qlikview/May2022/Subsystems/Client/Content/QV_QlikView/QlikView_Personal_Edition.htm

⁸² Adapted from: (1) S. Scott, '18 free and open source business intelligence tools', 2017. <https://logz.io/blog/business-intelligence-tools/> (accessed Jan. 21, 2023).

(2) R. Kaur, 'Best Free BI Software 2023', 2022. <https://www.selecthub.com/business-intelligence/free-business-intelligence-tools/> (accessed Jan. 21, 2023).

(3) The SMB Guide, 'Best Free Business Intelligence Software for 2023', 2022. <https://www.thesmbguide.com/free-business-intelligence-software> (accessed Jan. 21, 2023).

APPENDIX H: VERIFICATION EXTENSION

This section extends on the verification of the web-based monitoring and data visualisation tool, as presented in Section 3.2.6.2.

Table 39 to Table 41 showcase the percentage error when comparing the output of the web-based monitoring and data visualisation tool to the expected output generated in Excel for Incomers 2, 3, and 4 of POD C1. Figure 87 to Figure 92 present a visual comparison between the output of the tool and the output generated in Excel using the same input data.

Overall, the percentage error values of the incomers, as presented in Table 39 to Table 41, were 0% for all the data points during the comparison. Thus, a subsequent MAPE value of 0% was achieved for all the incomers of POD C1, indicating that the output generated by the tool matched the expected output generated in Excel. Furthermore, Figure 87 to Figure 92 visually illustrate the output comparison to confirm the accuracy indicated by the MAPE value 0%.

The web-based monitoring and data visualisation tool is, therefore, deemed verified based on the statistical accuracy represented by a MAPE value of 0%.

Table 39: Web-based monitoring and data visualisation tool output verification – Incomer 2

Output Verification			
Date & Time	POD C1 Incomer 2 Power Factor [Ratio]		Error [%]
	Tool Output	Excel Output	
07/08 00:00	0.99	0.99	0
07/08 00:30	1.00	1.00	0
07/08 01:00	1.00	1.00	0
07/08 01:30	0.99	0.99	0
07/08 02:00	1.00	1.00	0
07/08 02:30	1.00	1.00	0
07/08 03:00	0.99	0.99	0
.	.	.	.
.	.	.	.
.	.	.	.
08/08 06:00	0.95	0.95	0
08/08 06:30	0.98	0.98	0
08/08 07:00	0.98	0.98	0
08/08 07:30	0.98	0.98	0

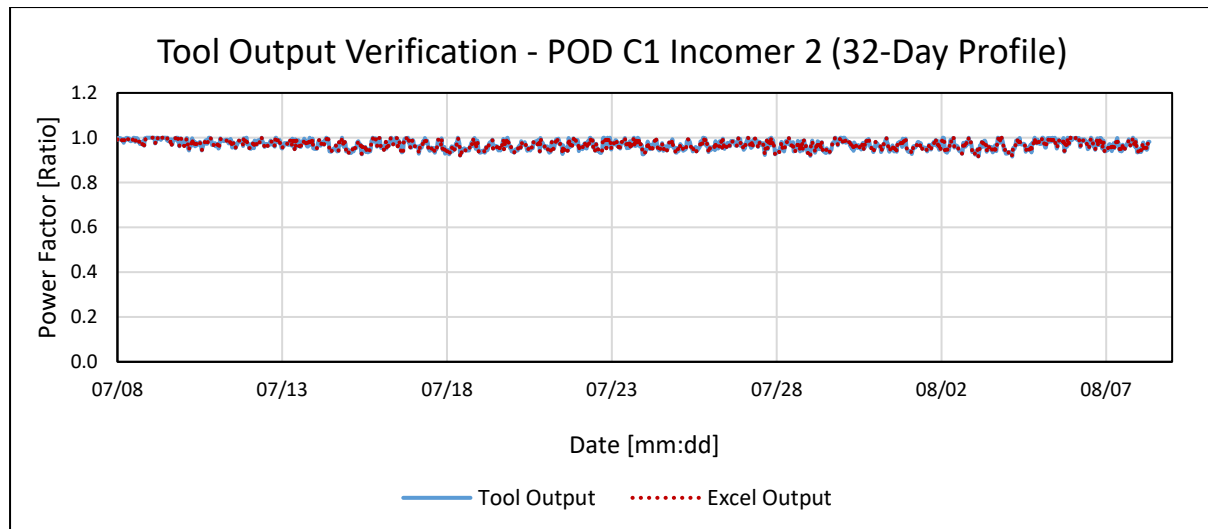


Figure 87: Web-based monitoring and data visualisation tool output verification – 32-day profile Incomer 2

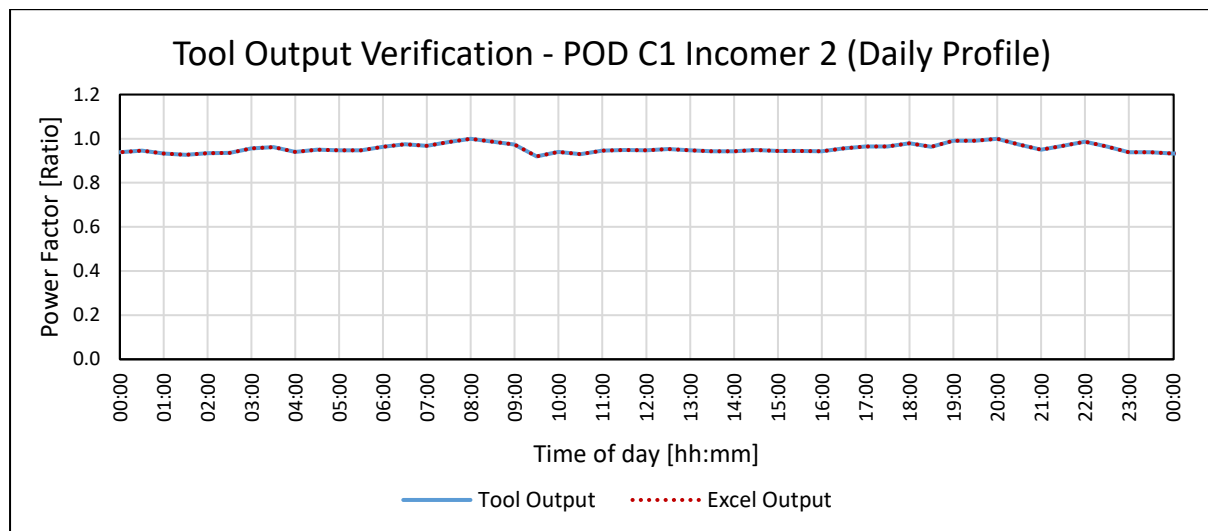
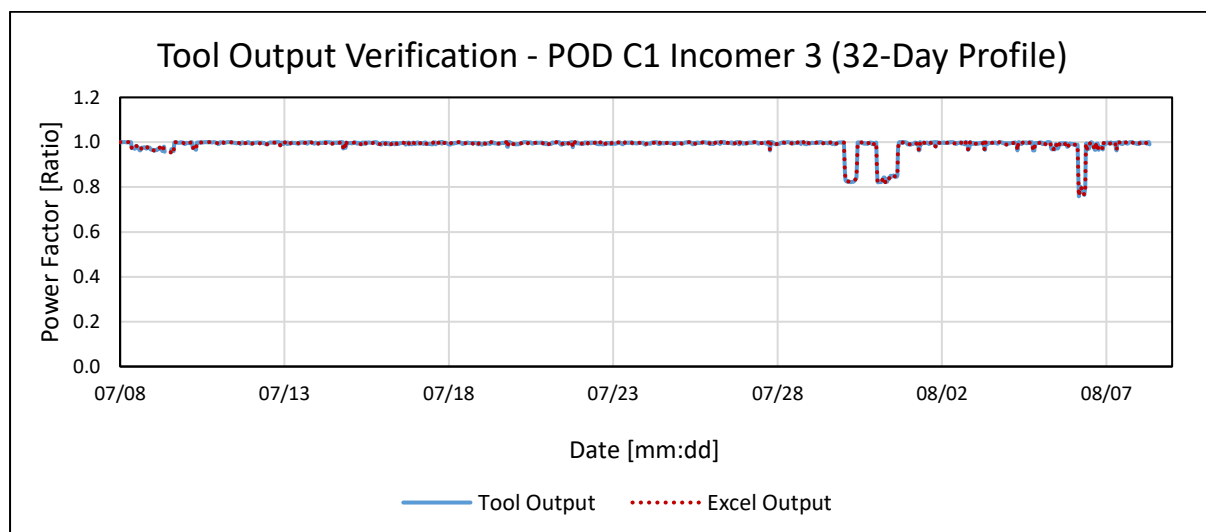


Figure 88: Web-based monitoring and data visualisation tool output verification – daily profile Incomer 2

Table 40: Web-based monitoring and data visualisation tool output verification – Incomer 3

Output Verification			
Date & Time	POD C1 Incomer 3 Power Factor [Ratio]		Error [%]
	Tool Output	Excel Output	
07/08 00:00	1.00	1.00	0
07/08 00:30	1.00	1.00	0
07/08 01:00	1.00	1.00	0
07/08 01:30	1.00	1.00	0
07/08 02:00	1.00	1.00	0
07/08 02:30	1.00	1.00	0
07/08 03:00	1.00	1.00	0
.	.	.	.
.	.	.	.
.	.	.	.
08/08 06:00	1.00	1.00	0
08/08 06:30	1.00	1.00	0
08/08 07:00	1.00	1.00	0
08/08 07:30	0.99	0.99	0

**Figure 89: Web-based monitoring and data visualisation tool output verification – 32-day profile Incomer 3**

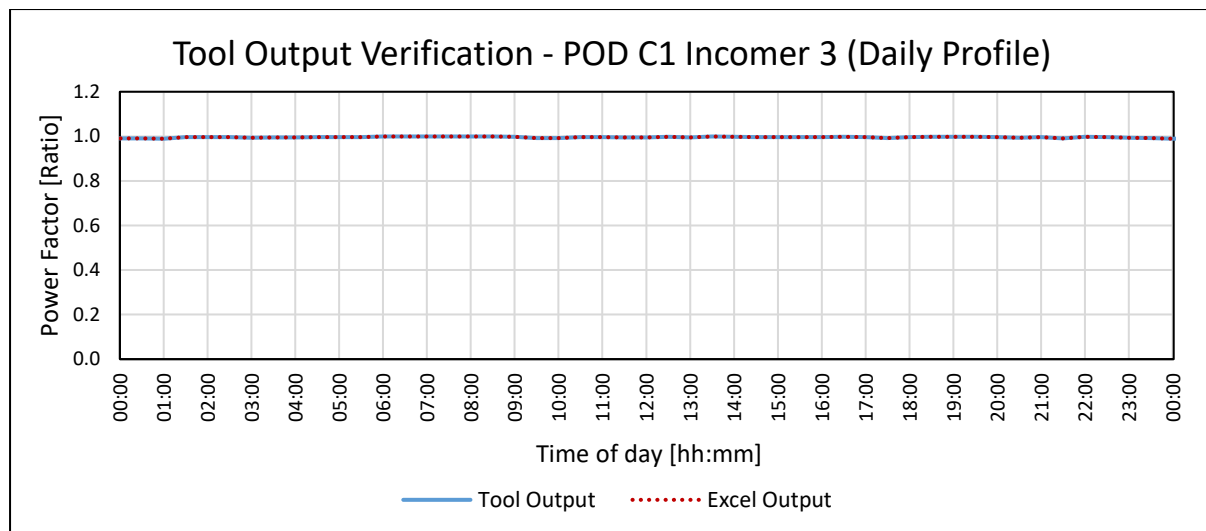


Figure 90: Web-based monitoring and data visualisation tool output verification – daily profile Incomer 3

Table 41: Web-based monitoring and data visualisation tool output verification – Incomer 4

Output Verification			
Date & Time	POD C1 Incomer 4 Power Factor [Ratio]		Error [%]
	Tool Output	Excel Output	
07/08 00:00	1.00	1.00	0
07/08 00:30	1.00	1.00	0
07/08 01:00	1.00	1.00	0
07/08 01:30	1.00	1.00	0
07/08 02:00	1.00	1.00	0
07/08 02:30	1.00	1.00	0
07/08 03:00	1.00	1.00	0
.	.	.	.
.	.	.	.
.	.	.	.
08/08 06:00	0.98	0.98	0
08/08 06:30	0.99	0.99	0
08/08 07:00	0.97	0.97	0
08/08 07:30	0.98	0.98	0

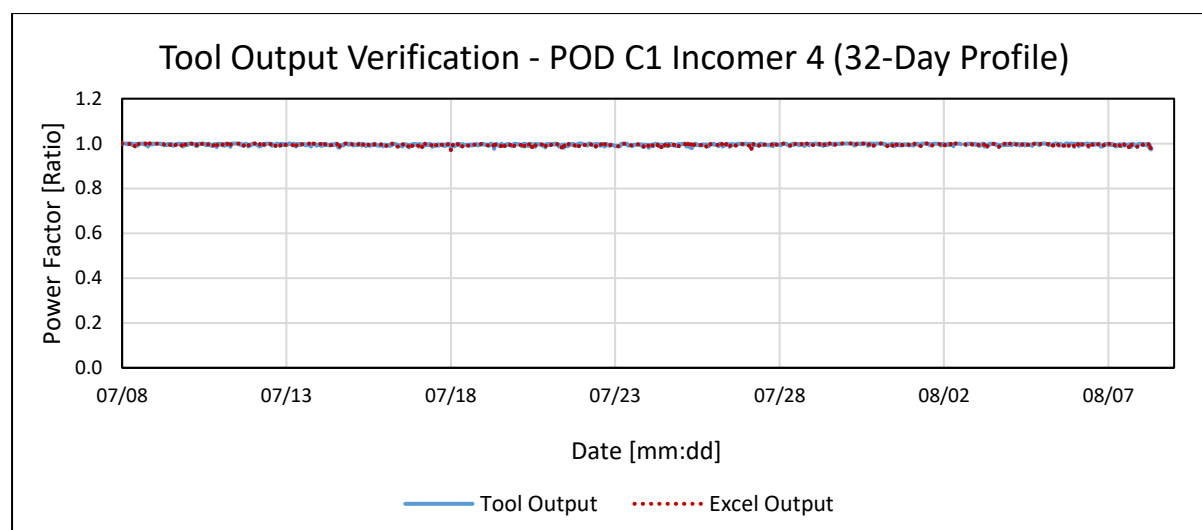


Figure 91: Web-based monitoring and data visualisation tool output verification – 32-day profile Incomer 4

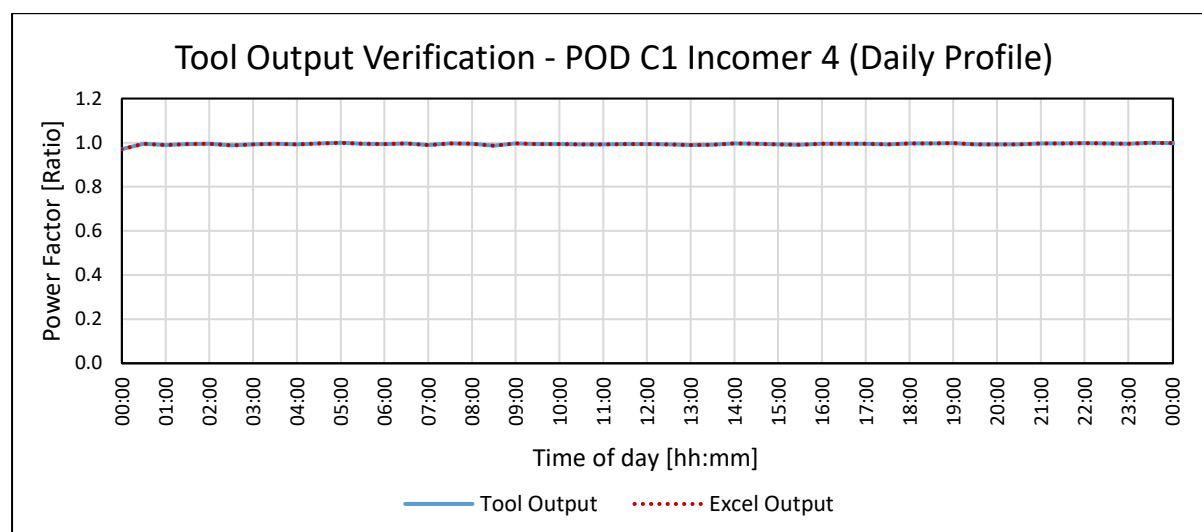


Figure 92: Web-based monitoring and data visualisation tool output verification – daily profile Incomer 4

APPENDIX I: VALIDATION EXTENSION

This section provides an overview of the year-on-year PF performance of the case study PODs within the June to September Eskom billing period (18 May to 18 September). The developed PFM tools were implemented on the case study PODs during the high-demand season of 2022.

Figure 93 to Figure 103 showcase the pre-implementation (2021) and post-implementation (2022) PF performance of the respective PODs.

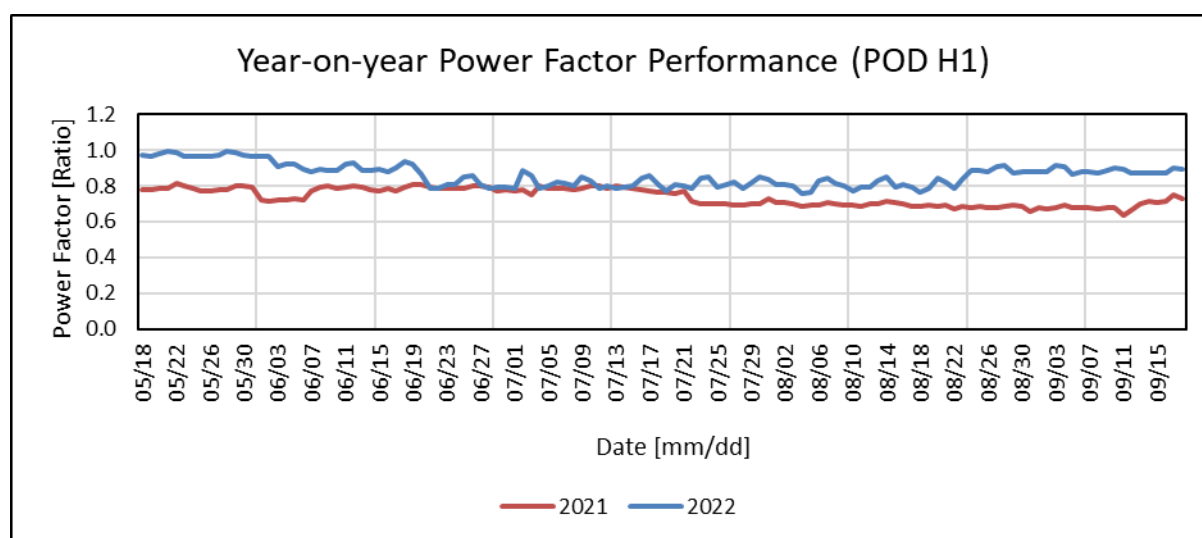


Figure 93: Year-on-year power factor performance of POD H1 – validation of tools

The improvement in the year-on-year PF performance of POD H1 is evident when examining Figure 93. POD H1 has two incomers available. In 2021, the total estimated capacitor bank downtime equated to 4 113 hours due to the capacitor bank at Incomer 2 being off for the whole high-demand season and was never reinstated within this period. Furthermore, the capacitor bank at Incomer 1 was deemed to be off between 22 July and 13 September 2021. Although a reduction in PF was seen between 1 June and 7 June 2021, this was due to a large reduction in the active power load during this period which negatively affected performance.

In 2022, there was no capacitor bank downtime recorded for Incomer 1 during the implementation period. However, reduced PF performance was identified on Incomer 2 from 3 June 2022. The issue was reported, and it was identified that the automatic controller (responsible for switching capacitance in and out of the system based on demand) was damaged. The control of the PFC system was, therefore, set to manual. A further reduction in PF performance was identified when the capacitor tripped on 20 June 2022. Upon further

inspection, personnel identified damage to the system. The system was back online from 13 September, but the automatic controller was not replaced within the examination period.

The PFM tools proved to facilitate proactive action being taken with regards to PF performance issues. The increased awareness of personnel and management assisted in expediting the reinstatement of capacitor banks when downtime was identified. Subsequently, the tools contributed to an estimated year-on-year reduction in capacitor bank downtime of 2 584 hours and the average PF increased from 0.75 to 0.87.

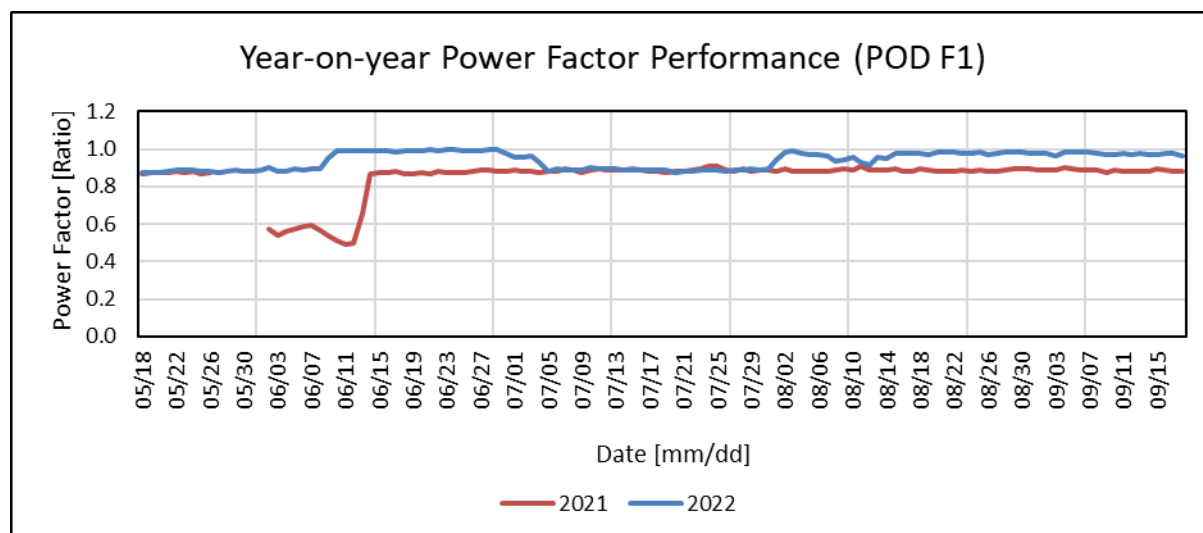


Figure 94: Year-on-year power factor performance of POD F1 – validation of tools

An improvement in the year-on-year PF performance was achieved for POD F1 as seen in Figure 94. POD F1 has three incomers available. The total estimated capacitor bank downtime equated to 4 784 hours in 2021. The capacitor banks of Incomers 2 and 3 were deemed to be inactive for the majority of the examination period which led to the high capacitor bank downtime and an average PF performance of 0.85. A substantial reduction in the PF performance was evident between 3 June and 14 in 2021. This was a combination of a large reduction in the active power consumption and capacitor bank downtime during this period.

In 2022, reduced PF performance was identified from 9 May at Incomers 1 and 3. This was reported to the relevant personnel. The capacitor banks were investigated and reinstated on 10 June 2022. Capacitor bank downtime at Incomer 1 was identified again on 26 June and was reinstated on 4 July. The capacitor banks at Incomers 2 and 3 were identified to be offline from 5 July. Upon communication with personnel, the decision was made to stop the banks due to concerns with voltage variation. Arrangements were made to have the capacitor banks investigated to identify and rectify the potential issue. The capacitor banks were reinstated from 1 August 2022 after inspection and maintenance concluded.

Reduced PF performance was identified at Incomer 1 from 7 August, but the capacitor bank was deemed to be active upon investigation. This reduction in PF performance may be attributed to a large increase in active power consumption between 7 and 14 August. The average active power consumption increased by about 4 MW during this period and the available PFC appears to not be designed to effectively compensate for the reactive energy produced at this load.

Overall, the estimated year-on-year capacitor bank downtime for POD H1 reduced by 1 425 hours and the average PF improved from 0.85 to 0.94 with the assistance of the PF monitoring, reporting, and notification tools.

Effective communication and action from personnel proved to be a challenge at the operations of POD H1 and F1 regarding PF issues. This can be attributed to new tools being adopted and incorporated as well as new communication channels being created. These difficulties are expected to improve as personnel become more familiarised with the tools and their awareness regarding the financial impact of poor PF performance is increased.

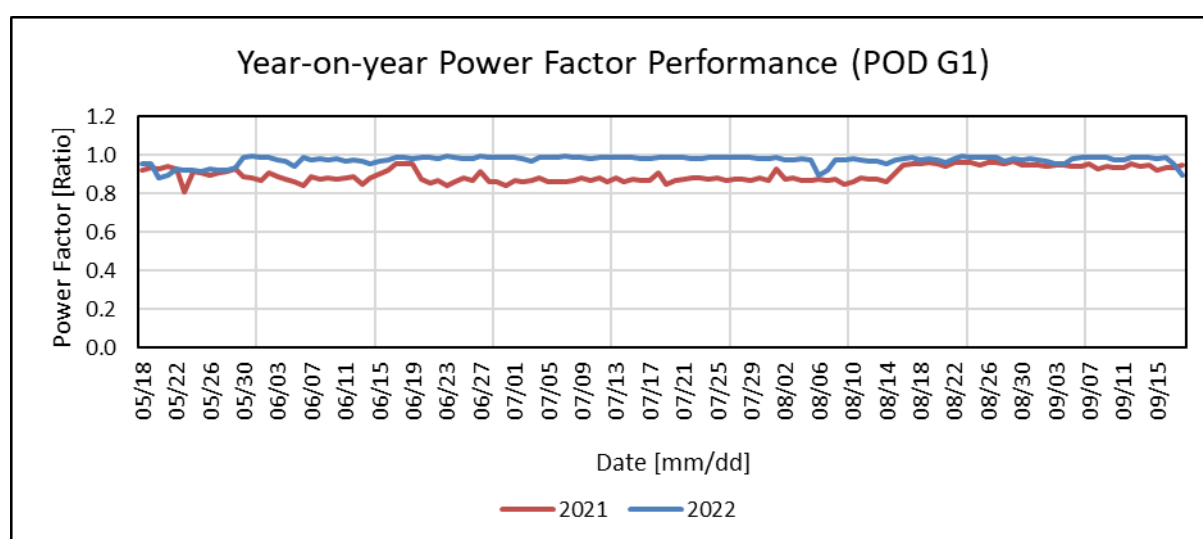


Figure 95: Year-on-year power factor performance of POD G1 – validation of tools

An improvement in the year-on-year PF performance was achieved for POD G1 as seen in Figure 95. POD G1 has four incomers available of which only Incomers 2, 3, and 4 are used. The total estimated capacitor bank downtime was 1 988 hours in 2021. Capacitor bank downtime was experienced at Incomer 2 until 20 June 2021 and the capacitor bank at Incomer 3 was off for most of the high-demand season, between 21 June and 15 August in 2021.

Reduced PF performance was identified in 2022 at Incomer 3 from 19 May. This was reported to the relevant personnel, and it was identified that the capacitor bank had tripped. The capacitor bank was reinstated after further inspection concluded on 29 May. The capacitor

bank at Incomer 3 tripped once again on 13 August and was reinstated on 15 August upon notifying personnel.

Reduced PF performance was identified on the weekends of 6 to 7 August and 17 to 18 September 2022, but all the capacitor banks were deemed active upon inspection. This may be attributed to a large reduction in the active power consumption caused by maintenance on the compressed air system on both the aforementioned weekends.

An estimated year-on-year capacitor bank downtime reduction of 1 734 hours was achieved with the implementation of the tools. This translated to an improved average PF performance of 0.90 (2021) to 0.97 (2022) across the high-demand season.

It is worth noting that a normalised year-on-year reduction of R135 000 was achieved in 2022 during the high-demand season with an additional surface fan active as seen with the increase in the average active power consumption of 1 MW in Table 33. This highlights the affect poor PF performance can have on the overall efficiency and operational costs of an operation.

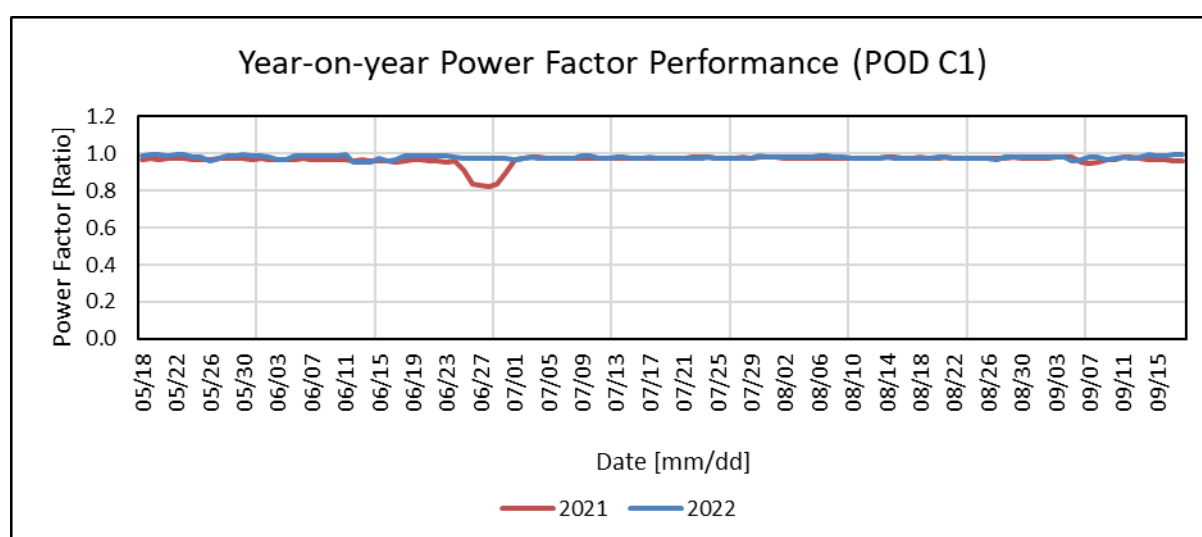


Figure 96: Year-on-year power factor performance of POD C1 – validation of tools

An improvement in the year-on-year PF performance was achieved for POD C1 as seen in Figure 96. POD C1 has four incomers available of which all four are utilised. The total estimated capacitor bank downtime of POD C1 equated to 592 hours in 2021. A large reduction in the PF performance was experienced between 26 June and 1 July 2021 due to multiple capacitor banks being offline. This, combined with the capacitor bank downtime of Incomer 1 from 13 September, contributed to the capacitor bank downtime experienced in 2021.

In 2022, reduced PF performance was identified from 2 June at Incomer 1 and was duly reported to personnel. Upon further investigation the capacitor bank was inactive and was reinstated on 5 June. Similarly, reduced PF performance was identified from 12 June. The reduction in performance was detected at Incomer 3 where the capacitor bank was offline. The capacitor bank at Incomer 3 was reinstated on 17 June.

The PFM tools facilitated swift identification of capacitor bank downtime and the reinstatement of the capacitor banks. This contributed towards minimising the capacitor bank downtime which resulted in an estimated year-on-year reduction in capacitor bank downtime of 418 hours, resulting in the year-on-year average PF performance of POD C1 improving from 0.97 (2021) to 0.98 (2022).

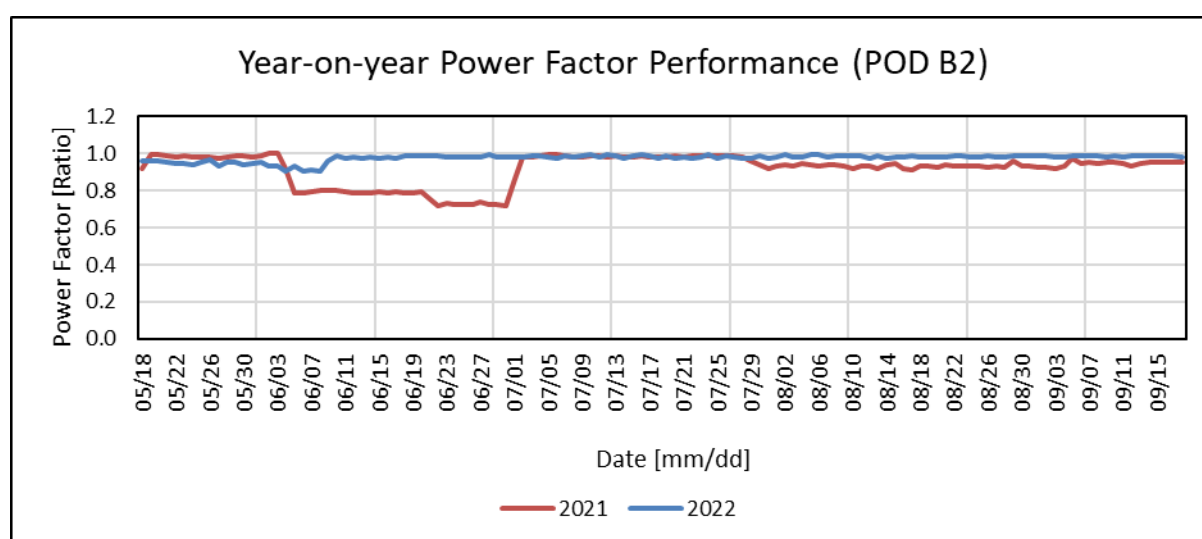


Figure 97: Year-on-year power factor performance of POD B2 – validation of tools

The improvement in the year-on-year PF performance of POD B2 is clear when examining Figure 97. POD B2 has three incomers available of which only Incomers 2 and 3 are active. In 2021 the estimated capacitor bank downtime equated to 653 hours. A substantial reduction in the PF performance is evident in 2021 between 4 June and 1 July. This can be attributed to capacitor bank downtime at incomer 3 during this period. A reduction in PF performance was also experienced from 29 July. This may be attributed to a low active power consumption at Incomer 2. The active power consumption at Incomer 2 reduced from around 1.3 MW to 300 kW during this period, presumably outside the design range of the PFC system.

The PF performance was more stable in 2022. Reduced PF performance was identified from 3 June 2022, more specifically at Incomer 3, and was reported to the relevant personnel. The capacitor bank reportedly tripped and was inspected before being reinstated on 9 June 2022.

The developed PF tools assisted in achieving a year-on-year improvement in the average PF performance of POD B2. The average PF improved from 0.92 (2021) to 0.97 (2022).

PODs H1, F1, G1, C1, and B2 saw a reduction in the estimated capacitor bank downtime with the PFM tools implemented in 2022, contributing to improved POD power factors within the high-demand season and resulting in reduced reactive energy charges and excess demand charges as outlined in Section 3.2.6.3.

There is still room for improvement pertaining to capacitor bank downtime. There appears to be a lack of urgency in terms of investigating the capacitor banks on the operation when reduced PF performance has been identified. This may be attributed to a lack of awareness from personnel with regards to the potential impact poor PF performance can have on the electricity costs of an operation.

Therefore, educating personnel may prove to benefit the initiative of minimising capacitor bank downtime and improving PFM. A maintenance tracking or clocking system should be considered as mentioned in Section 4.2. This could involve personnel having to report daily whether the status of the capacitor banks have been checked, as this is already part of the electrician's daily duties. This, in turn, may assist in earlier fault detection which may prevent prolonged capacitor bank downtime due to a breakdown in the future.

However, PODs A2, B1, I1, E1, A1, and D1 did not experience any capacitor bank downtime during the high-demand seasons of 2021 and 2022. The PF performance of these PODs were similar when compared year-on-year. The PF performance profiles of these PODs are presented in Figure 98 to Figure 103.

The brief reductions in PF performance visible when inspecting the PF performance profiles of PODs B1, I1, E1, and D1 may be attributed to scheduled maintenance. During these periods, systems are stopped, which results in large variations in the active power consumption and may, therefore, cause an abrupt decline in PF performance.

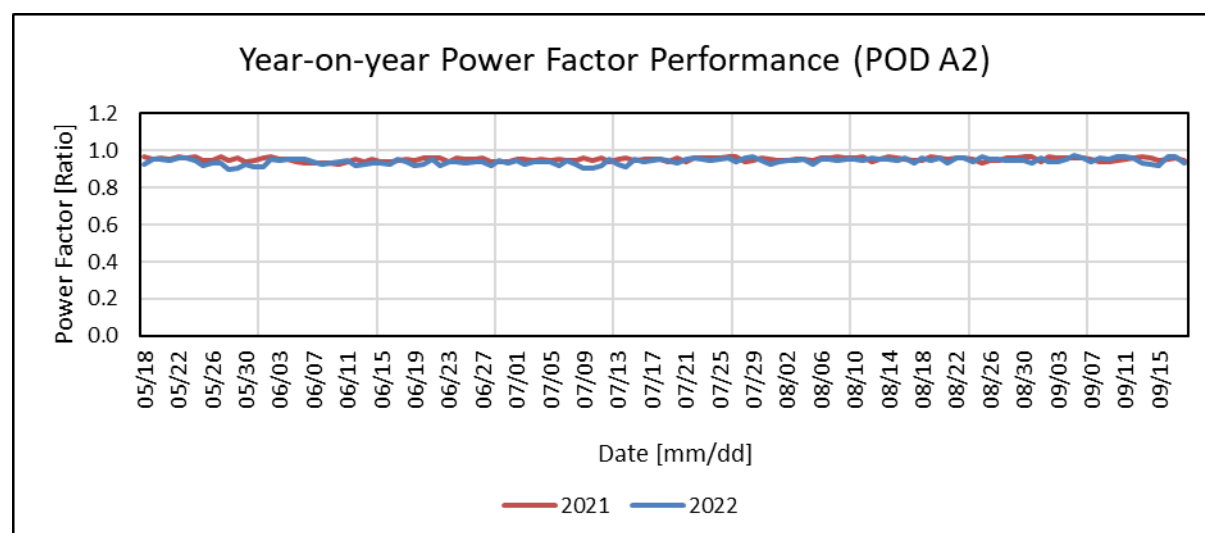


Figure 98: Year-on-year power factor performance of POD A2 – validation of tools

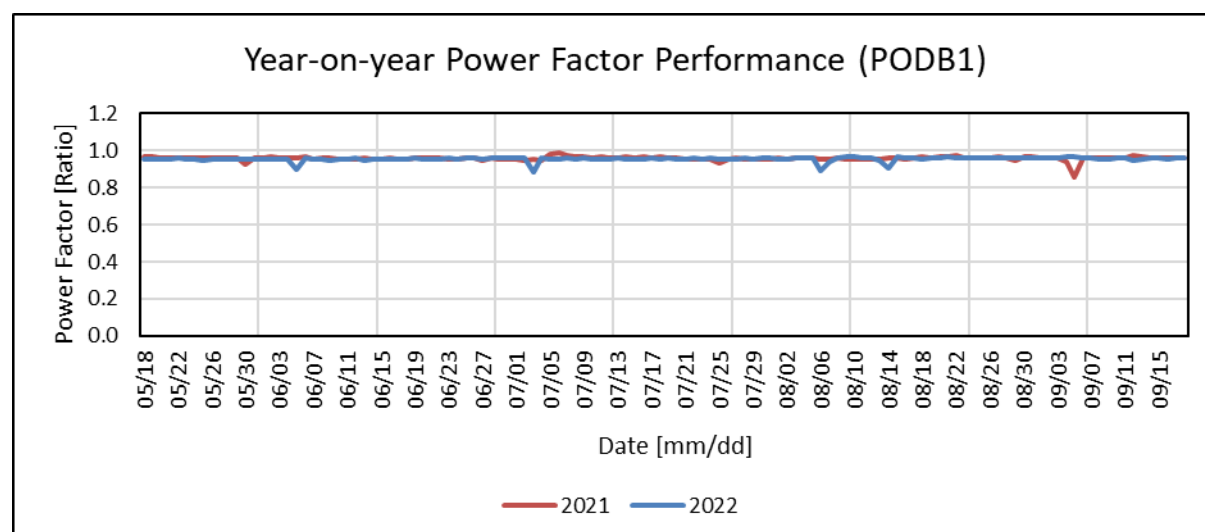


Figure 99: Year-on-year power factor performance of POD B1 – validation of tools

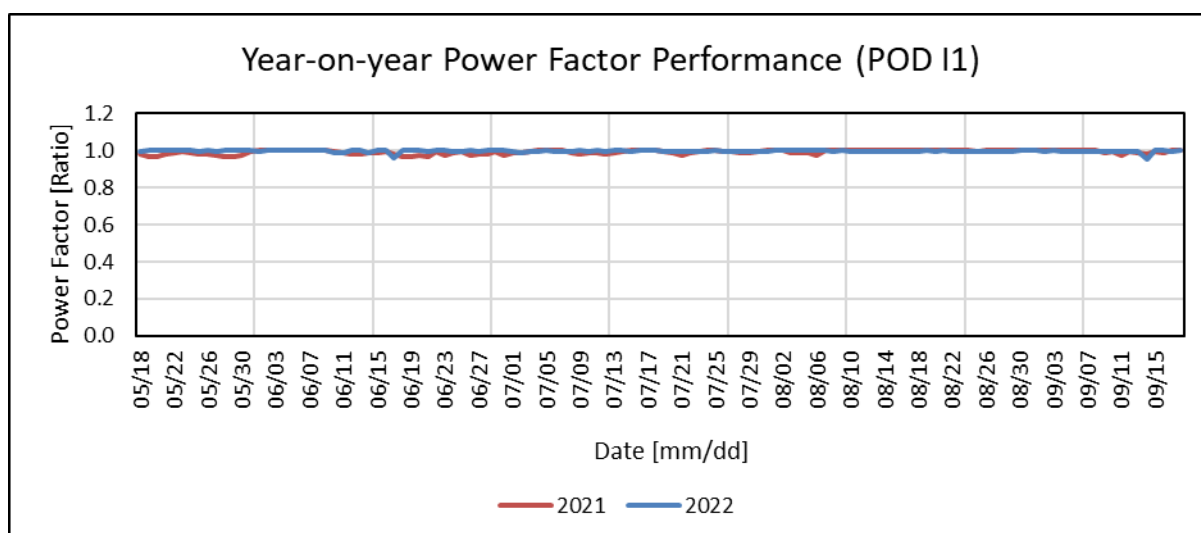


Figure 100: Year-on-year power factor performance of POD I1 – validation of tools

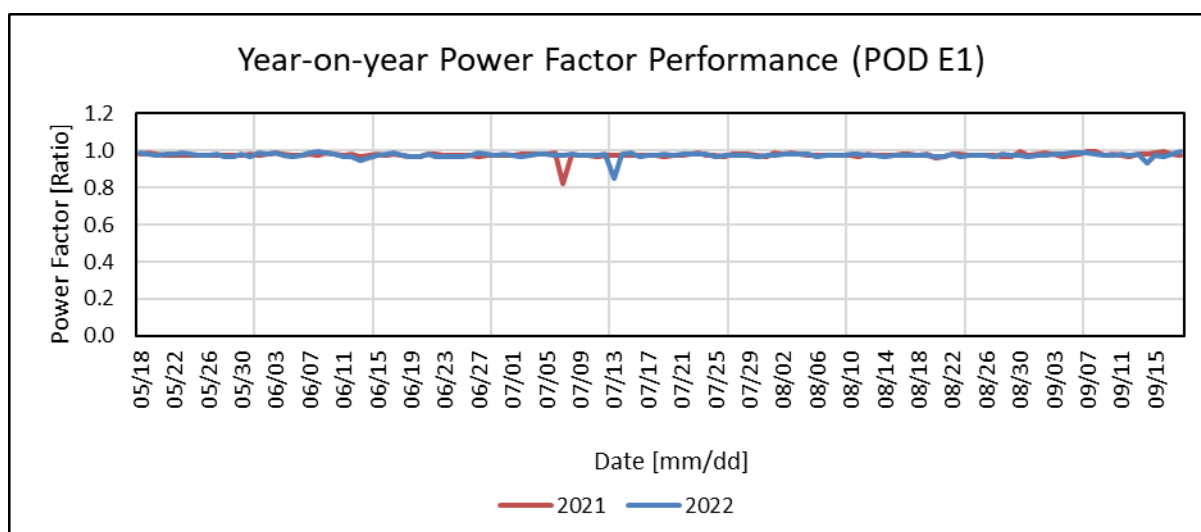


Figure 101: Year-on-year power factor performance of POD E1 – validation of tools

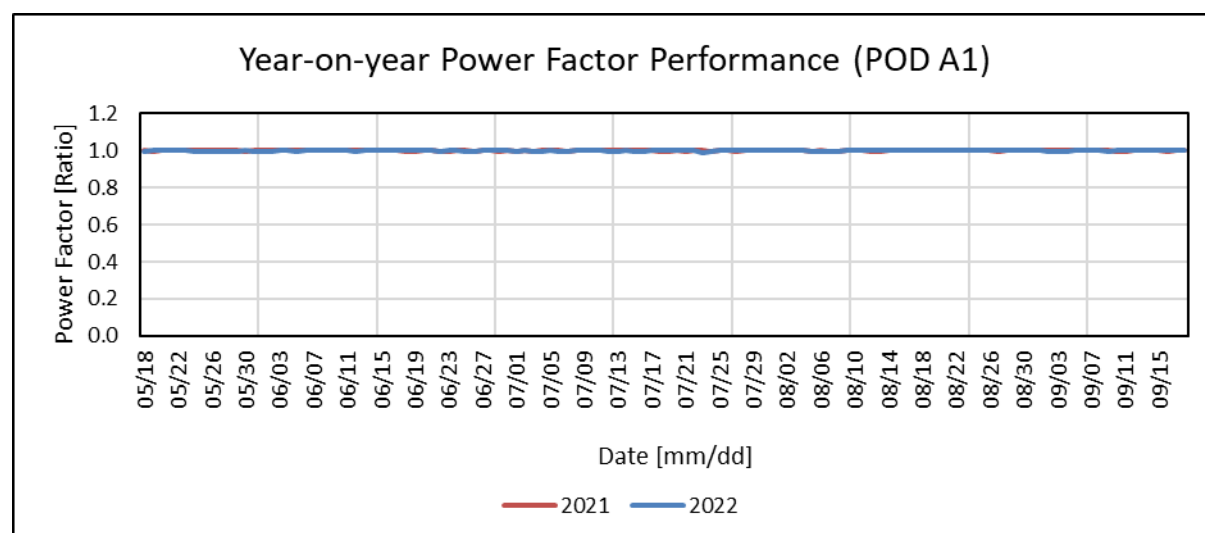


Figure 102: Year-on-year power factor performance of POD A1 – validation of tools

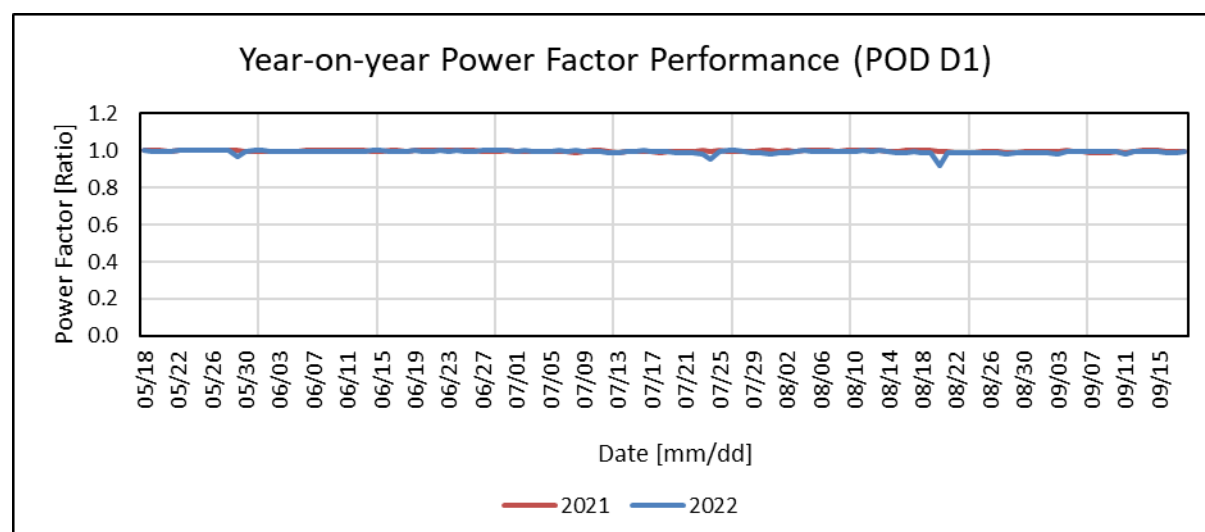


Figure 103: Year-on-year power factor performance of POD D1 – validation of tools

APPENDIX J: POWER FACTOR TRACKING SHEET EXAMPLES

This section provide examples of the PF performance tracking and limit tracking sheets.

Power Factor Monitoring								
Date	Operation POD	Power Factor Correction Issues/Capacitor Bank Inactive						
		Identified	Communicated	Resolved	Average POD PF Impact [Ratio]		Status	Comments
					Before	After		
2023/05/22	PODs	Yes	Yes	Yes	0.95	0.98	Resolved	Confidential
2023/05/31		Yes	Yes	Yes	0.70	0.99	Resolved	
2023/06/02		Yes	Yes	Yes	0.65	0.87	Resolved	
2023/06/05		Yes	Yes	Yes	0.95	0.99	Resolved	
2023/06/07		Yes	Yes	Yes	0.94	0.97	Resolved	
2023/06/14		Yes	Yes	Yes	0.85	0.98	Resolved	
2023/06/20		Yes	Yes	Yes	0.88	0.96	Resolved	
2023/06/21		Yes	Yes	Yes	0.95	0.99	Resolved	
2023/07/04		Yes	Yes	Yes	0.95	0.99	Resolved	
2023/07/06		Yes	Yes	Yes	0.94	0.97	Resolved	
2023/07/17		Yes	Yes	Yes	0.82	0.97	Resolved	
2023/07/27		Yes	Yes	Yes	0.84	0.93	Resolved	
2023/08/02		Yes	Yes	Yes	0.92	0.98	Resolved	
2023/08/16		Yes	Yes	Yes	0.96	0.98	Resolved	
2023/08/17		Yes	Yes	In progress	0.94		Solution Implementation	

Figure 104: POD power factor tracking example

Power Factor POD Alarm Updates					
Date	Operation POD	POD PF Limit [Ratio]		Average PF [Ratio]	Reason
		Before	After		
2023/07/07	PODs	0.95	0.97	0.99	Improve identification of capacitor bank downtime. Alarm did not always trigger when the capacitor bank at incomer #3 tripped (average POD power factor dropped to between 0.95 and 0.96).
2023/07/08		0.94	0.96	0.97	Improve identification of capacitor bank downtime. Alarm did not trigger during capacitor bank downtime at incomer #3.
2023/07/17		0.92	0.96	0.97	Improve alarm accuracy. POD power factor performance improved from 05 July (average POD power factor increased from 0.94 to 0.97) - improved PFC at incomer #3.
2023/07/17		0.95	0.97	0.98	Improve alarm accuracy. POD power factor performance improved from 04 June (average POD power factor increased from 0.95 to 0.98) - improved PFC at incomer #6.
2023/07/17		0.90	0.94	0.96	Improve alarm accuracy. POD power factor performance improved from 12 July (average POD power factor increased from 0.92 to 0.96) - all banks tested and active.
2023/07/24		0.88	0.96	0.98	Improve alarm accuracy. POD power factor performance improved from 17 July (average POD power factor increased from 0.92 to 0.96) - all banks tested and active.
2023/07/31		0.80	0.86	0.93	Improve alarm trigger. Reduced power factor performance was identified from 27 July. The limit was too low and has been adjusted for improved alarm trigger.

Figure 105: POD power factor limit sheet example