Developing a dynamic operational energy management strategy for energy intensive industries

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Abstract

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Fossil fuels are likely to supply most human energy needs for the 21st century. However, these fuels are exhaustible and have adverse environmental effects when combusted. To reduce the negative environmental effects, the onus is on energy consumers to reduce their energy consumption by being more energy efficient. Industry is responsible for approximately 29% of world energy consumption. As international studies have estimated that efficiency improvements of between 5% and 30% are possible in this sector, it has become a prime target of policy and improvement initiatives globally.

A history of low energy prices in South Africa has resulted in poor energy management practices and inefficient energy use. With recent energy price increases, specifically electricity prices increasing 271% since 2000, South African industry must improve its energy efficient practices. Due to a strained economy, there is no capital for large energy efficiency improvement projects, but operational energy management can provide energy savings of 5% with very little capital outlay.

Operational energy management consists of measurement, analysis and feedback to reduce operational energy waste. The foundation is to measure energy usage accurately enough that the derived data is reliable. This data must be analysed, resulting in information regarding the actual energy performance. Finally, effective feedback ensures that the right person receives the right performance information, empowering the person to act and thereby improve energy performance.

Existing practices in South African industry relevant to operational energy management were reviewed and found to be not of a suitable level of maturity yet. Several additional barriers were identified, such as a lack of knowledge on how to approach applying operational energy management to a complex industrial facility, how to effectively implement it, and how to manage energy data. It was also evident that most existing research in this field is either very high level, or focuses on a very specific sub-component of operational energy management.

No literature could be found that provides a comprehensive methodology for implementing operational energy management in industry. Most literature focuses either on high level guidance and policies, or offers very low level and technical information. Available literature was not vertically integrated, meaning that only a part of the process (such as analysis) was covered with no support for integration with other steps. The need for a comprehensive methodology for the South African energy intensive industry was identified. This study develops a system-based approach for integrated operational energy management in South Africa.

A methodology for implementing energy measurement is developed. This methodology provides a systematic process for ensuring the correct measurement of important energy streams. A method to effectively manage measurement quality, thereby ensuring that measurements are verified, is also developed. Effective management of energy data is implemented, ensuring that the provided data is reliable and available where needed. The second part of the methodology is performing accurate analyses. This process uses a systematic process to accurately identify energy drivers acting on each system in the facility. This information and data are then used to develop a performance evaluation model of the system, based either on mathematical principles or historical and metadata, depending on available infrastructure. Finally, a methodology for effective operational energy management feedback is developed. This process is designed to ensure that feedback is integrated into facility operations by incorporating all relevant stakeholders. Guidelines are developed to ensure that the developed feedback is effective at promoting improved energy performance.

This comprehensive methodology was implemented on a South African gold mining group as a case study, which demonstrates the methodology, identifies key challenges and validates the proposed methodology. Validation is done by measuring energy cost savings achieved by the group. The implementation contributes to a total of R41.9 million in cost savings in specific isolated cases for one year. Furthermore, through improved operational control, a R25.3 million annual cost saving was realised on the group's total bill.

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Table of Contents

Abstract ii
Acknowledgements iv
List of figures vii
List of tables x
Nomenclature xi
Chapter 1 Introduction 1
1.1 Preamble 1
1.2 The global need for industrial energy management 1
1.3 Energy supply and use in South Africa 2
1.4 Energy management 5
1.5 System-based approach 13
1.6 Need for study 14
1.7 Contributions of study 15
1.8 Outline of thesis 20
Chapter 2 Operational energy management concepts and literature 22
2.1 Preamble 22
2.2 Accurate measurement of energy use 22
2.3 Useful analysis of energy data 38
2.4 Correct use of energy feedback 53
2.5 Requirements 64
2.6 Conclusion 68
Chapter 3 Developing a system-based approach for operational energy management 69
3.1 Preamble 69
3.2 Overview of the system-based concept 69
3.3 New energy measurement methodology for operational energy management 71
3.4 Development of new methodology for energy performance analysis 92
3.5 New energy feedback strategy 103
3.6 Conclusion 111
Chapter 4 Case study – Implementation 113
4.1 Preamble 113
4.2 Overview of implementation 114
4.3 Measurement and data management 115

4.4 Data analysis 132
4.5 Feedback 149
Chapter 5 Case study – Results 153
5.1 Overview 153
5.2 Results from improved budget methodology 153
5.3 Specific results 156
5.4 Evaluation of group results 161
5.5 Conclusion 167
Chapter 6 Conclusions and recommendations 168
6.1 Overview of study 168
6.2 Contributions 171
6.3 Limitations and further work 172
References 174
Appendix A 185
Appendix B 197

List of figures

Figure 1: Global energy consumption by sector for 2013 [5] 2
Figure 2: Eskom annual price increases for Megaflex tariffs versus South Africa's inflation rate [31] 4
Figure 3: ISO 50001-compliant energy management system [39] 7
Figure 4: Operational energy management as a subset of an energy management system......................... 9
Figure 5: Example of improved energy performance through reduced variability 10
Figure 6: Example of improved energy performance by reducing artificial inflation 10
Figure 7: Example of improved energy performance through improved operational efficiency.............. 11
Figure 8: The operational energy management cycle 13
Figure 9: Examples of meters, measurements and data 23
Figure 10: Relative energy consumption of different mine sub-systems 29
Figure 11: Isolated energy data metering networks 34
Figure 12: Temporal scale of decision-making in manufacturing (adapted from [66]) 36
Figure 13: Graphic illustration of vertical integration of processes into a single facility or plant 39
Figure 14: Example of hourly energy consumption of a system 40
Figure 15: Baseline and actual performance used to determine energy savings 42
Figure 16: Energy budget and target versus actual performance 44
Figure 17: Energy wastage is identified more easily by understanding energy drivers 46
Figure 18: Example of the cumulative sum technique 47
Figure 19: Capturing of existing inefficiencies using a black-box characterisation 50
Figure 20: Example of KPIs developed by May *et al*. [65] 51
Figure 21: Basic structure of a feedback loop 53
Figure 22: Basic diagram of feedback used in operational energy management 54
Figure 23: Full scope of energy feedback 54
Figure 24: Exception handling practised in industry 56
Figure 25: Energy feedback routed through energy management team 56
Figure 26: Model for energy reporting (adapted from [42]) 60
Figure 27: Operational energy management process overview 69
Figure 28: A production facility illustrated as an arrangement of systems 70
Figure 29: Methodology for energy metering 72
Figure 30: Basic systematic process for identifying metering locations 72
Figure 31: Illustration of methodology terms 73
Figure 32: Example of metering points available for a typical facility 74
Figure 33: Common energy distribution and use in industry 76
Figure 34: Step 1 – identify energy carriers transferred across facility boundary 77
Figure 35: Step 2 – identify the entry point of each energy carrier into plant systems and storage areas . 78
Figure 36: Step 3 – determine the points where energy carriers exit systems 79

Figure 37: Step 4 – follow energy carriers to the next system ... 80
Figure 38: Next iteration of Step 3 – determine where energy carriers exit systems ... 81
Figure 39: Methodology applied to captive energy sources ... 82
Figure 40: Illustration of energy carriers flowing between end users ... 84
Figure 41: Basic methodology for metering quality ... 85
Figure 42: Process for selecting measurement points ... 86
Figure 43: Analysis methodology for achieving SANS 50010-compliant energy content data and verified CO_2e data ... 87
Figure 44: Overview of data management methodology ... 88
Figure 45: Overview of data integrity methodology ... 88
Figure 46: Profiles of common energy data problems ... 89
Figure 47: Data communication layout for operational energy management ... 90
Figure 48: Structure for feedback data source ... 91
Figure 49: Basic process for data analysis ... 93
Figure 50: Step 1 – identify end products and systems ... 94
Figure 51: Step 2 – identify next layer of systems ... 95
Figure 52: Step 3 – continue process until inputs cross facility boundary ... 95
Figure 53: Collect information step ... 96
Figure 54: Identify energy drivers ... 97
Figure 55: Characterisation of energy-consuming system ... 98
Figure 56: Characterisation improves as understanding of underlying system is improved ... 99
Figure 57: Characterise energy driver relationship ... 100
Figure 58: Basic methodology for historical and metadata based model ... 102
Figure 59: Basic methodology for feedback development ... 103
Figure 60: Basic process for stakeholder identification ... 104
Figure 61: Typical hierarchy of industrial companies ... 105
Figure 62: Basic process for developing feedback for each stakeholder ... 106
Figure 63: Overview of method for developing feedback ... 107
Figure 64: Guideline for feedback based on number of systems and degrees of separation ... 108
Figure 65: Scale of feedback levels at different appropriate temporal intervals ... 109
Figure 66: Frequency and timespan of feedback compared with decision-making level ... 110
Figure 67: Spectrum of data analysis for feedback ... 110
Figure 68: Analysis guideline based on levels of separation ... 111
Figure 69: Electricity consumption by check metering and utility ... 116
Figure 70: Typical gold mine electricity consumption distribution [98] ... 117
Figure 71: GM Group 1, Site 1, Shaft 1 annual electricity consumption breakdown by system ... 119
Figure 72: Electricity demand for Site 1, Shaft 1 sub-systems and main incomer check meter ... 119
Figure 73: Site 4 electric power profile of sub-meters and check meter on main incomer ... 122
Figure 74: Data loss by sub-system for Site 4 ... 123

Figure 75: Layout of sub-metering data communication network for GM Group 1 127

Figure 76: Site 4 compressor system electric power profile for 31 May 2016 129

Figure 77: Layout of data centralisation and management system implemented for GM Group 1 130

Figure 78: Visual representation of data loss analysis 131

Figure 79: Comparison of monthly budget and actual electricity consumption for three-year period for Site 1, Shaft 1 133

Figure 80: Comparison of budget and actual electricity consumption for the systems of Site 1, Shaft 1 for 2013 and 2014 134

Figure 81: Site 1, Shaft 1 compressor system electricity demand profile for weekdays 135

Figure 82: Comparison of budget and actual cost profile for Site 1, Shaft 1 136

Figure 83: Average daily electricity consumption for Site 1, Shaft 1 for different weekdays 137

Figure 84: Regression analysis for GM Group 1 operations comparing monthly production with electricity consumption 140

Figure 85: Weekday average electricity demand for the winder system of Site 7, Shaft 1 142

Figure 86: Average weekday electric power profile for Site 5, Shaft 1 pumping system 143

Figure 87: Monthly power consumption and average temperature for refrigeration system for Site 5, Shaft 2 144

Figure 88: Average daily compressed air flow demand and network pressure for Site 4 146

Figure 89: Monthly total electricity consumption for Site 4's hostels 147

Figure 90: Budget development based on historical data for seasonal systems 148

Figure 91: Feedback development process for GM Group 1 149

Figure 92: Information and control structure for GM Group 1 energy management 150

Figure 93: Stakeholder structure for GM Group 1 151

Figure 94: Comparison of budget model errors for GM Group 1 by system 154

Figure 95: Comparison of budget model errors for GM Group 1 by site 155

Figure 96: Site 3 ventilation fan daily electricity consumption from February to July 2016 156

Figure 97: Daily total electricity budget and actual consumption for Site 2 ventilation fans 158

Figure 98: Monthly average performance of energy saving initiative 159

Figure 99: Improved TOU performance 162

Figure 100: Example of improved control and reduction in outliers for Site 1's compressed air system 163

List of tables

Table 1: Survey of South African companies and energy managers 5

Table 2: Energy carriers typically found in South African industry 24

Table 3: Summary of literature regarding energy measurement scope 28

Table 4: Quantity and ancillary measurements for energy carriers used in industry 31

Table 5: Summary of literature regarding energy measurement quality 33

Table 6: Summary of literature regarding energy data management 37

Table 7: Summary of literature regarding energy data analysis 52

Table 8: Survey of feedback employed in South African industrial companies 55

Table 9: Summary table of information required by different recipients (adapted from [89]) 59

Table 10: Information needs for different planning levels (adapted from [42]) 60

Table 11: Summary of literature regarding energy performance feedback 64

Table 12: Existing work and requirements for operational energy management 66

Table 13: Typical systems found in several industries 69

Table 14: Summary of results of Step 1 77

Table 15: Summary of results of Step 2 78

Table 16: Summary of results of Step 3 79

Table 17: Summary of results from Step 4 80

Table 18: Summary of results from second iteration of Step 3 81

Table 19: Summary of results of energy carrier audit process 82

Table 20: Example of systems and energy drivers in industry 99

Table 21: Examples of systems and operators in industry 105

Table 22: Examples of systems and operators in industry 106

Table 23: Feedback development criteria 111

Table 24: Summary of operations in GM Group 1 113

Table 25: Breakdown of Site 1’s estimated annual electricity consumption by system 118

Table 26: Results from sub-metering verification 120

Table 27: Installed capacity and expected load factor of hoisting system on Site 2 122

Table 28: Priority list for Site 4’s sub-metering 124

Table 29: Annual electricity consumption and cost for unmetered systems 125

Table 30: Statistical analysis of macro energy drivers for GM Group 1 139

Table 31: Summary of typical sub-systems present on South African gold mines 141

Table 32: Difference between actual values and existing group budgets with improved budgets 153

Table 33: Performance impact of daily feedback report for GM Group 3 160

Table 34: List of sites and systems excluded from statistical analysis 164

Table 35: Breakdown of reduction in outliers by system 165

Table 36: Breakdown of reduction in outliers by site 165

Table 37: Summary of change in group energy intensity 166

Nomenclature

CEO	Chief Executive Officer
CFO	Chief Financial Officer
DSM	Demand Side Management
ESCo	Energy Service Company
ETSU	Energy Technology Support Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GW	Gigawatt
GWh	Gigawatt-hour
HVAC	Heating, Ventilation and Air-conditioning
kPa	Kilopascal
KPI	Key Performance Indicator
kWh	Kilowatt-hour
m^3/h	Cubic Metres per hour
MJ	Megajoule
mm	Millimetre
MW	Megawatt
MWh	Megawatt-hour
NMD	Notified Maximum Demand
ROI	Return on Investment
SEU	Significant Energy User
TOU	Time-of-use

Chapter 1 Introduction

1.1 Preamble

This chapter will serve as an introduction to this study. As this study principally deals with energy management in industry, the importance and relevance of this topic will be established first. Next, operational energy management will be introduced as a basic first step to energy management. The shortfalls in literature and practice regarding operational energy management will be identified. From this, the objectives and contributions of this study to existing knowledge will be established. Finally, an overview of the thesis will be given.

1.2 The global need for industrial energy management

Access to energy in a form that is easy to use (such as electricity) is considered a marker of a society's level of development [1]–[4]. Global demand for easily accessible energy has been escalating steadily, especially in industrialising countries such as China and India [5]. In 2013, 81% of global energy was supplied through fossil fuel combustion [5]. These fossil fuels are scarce, can be exhausted and their combustion has adverse environmental effects such as greenhouse gas (GHG) emissions that lead to global warming [4], [6].

Many developed countries aim to replace fossil fuels with renewable energy sources [4], [7], [8]. However, doing so is an expensive process that cannot be completed quickly [9]. Simultaneously, many developing countries are unwilling to bear the cost of expensive renewable energy sources and instead primarily use cheaper fossil fuel energy sources [10]. It is estimated that renewable sources will only make up a quarter of electric power production by 2020 [9], and by 2040 approximately a quarter of world energy will be from low carbon sources [11]. The problem of fossil fuel exhaustion and GHG emissions will not be solved on the supply side in the short term.

Thus, the onus has fallen on the energy user to increase the effectiveness at which energy is consumed [12]. A significant amount of research and funding has been allocated to improving the energy efficiency of various technologies and increasing awareness [13]. Figure 1 shows a breakdown of global energy consumption[1] by sector for 2013.

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[1] In this document, the meaning of energy consumption will be taken, as it is defined in ISO 50001, to mean the amount of energy consumed. Energy use will refer to the specific application being referred to.

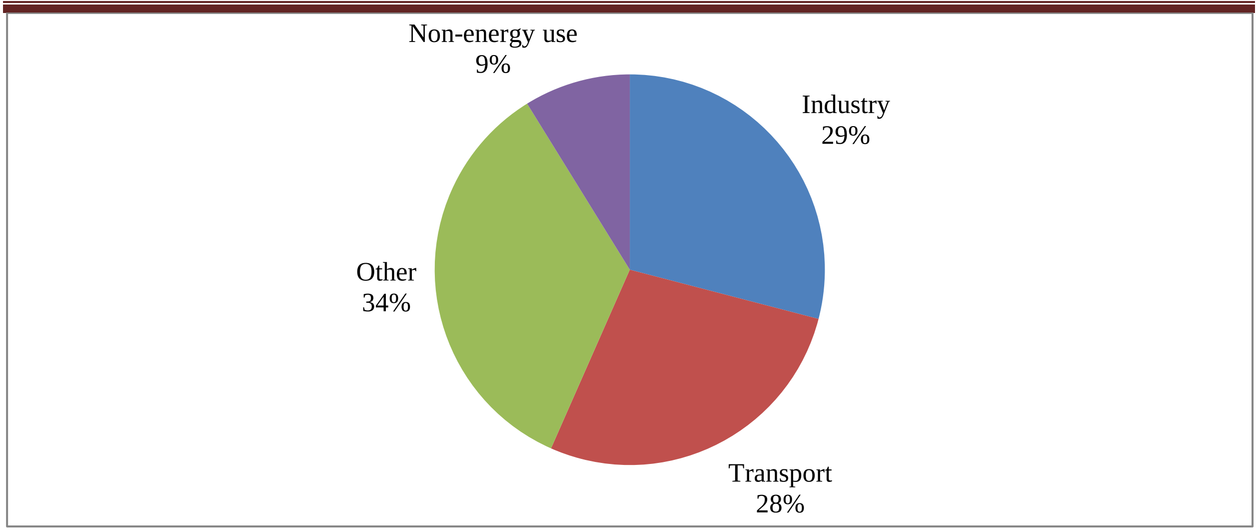

Figure 1: Global energy consumption by sector for 2013 [5]

As Figure 1 shows, industry is responsible for 29% of global energy consumption [5]. Studies have indicated that there is significant potential for energy savings in industry [14], [15]. Saving estimates range between 5% and 30% [16], [17]. Thus, industry has become the target of legislature, incentives and policies regarding energy management in many countries [13], [18], indicating that industry is expected to contribute a significant portion of global energy savings [13].

Due to continuing research, processes and technological improvements for improved energy efficiency are available in many industries [19], [20]. However, these changes typically require capital investments, and there is a significant gap between the financial feasible interventions available and those that have been applied in industry [21]. Many authors have conducted research to identify the causes of this energy efficiency gap [22], [23]. These studies have shown that some of the primary drivers are related to a lack of capital funding and managerial support [24], [25].

It has been shown in many sectors that energy savings can be achieved by implementing an effective energy management system [26]. Although investments in energy efficient technologies form a part of an energy management system, significant savings can be achieved through actions of “good housekeeping” [18].

1.3 Energy supply and use in South Africa

South Africa is a developing country still heavily dependent on fossil fuels for energy supply [27], [28]. South Africa’s primary electric utility, Eskom, predominantly uses coal-fired electricity generation plants.[2] Recently, South Africa's government has also started procuring nuclear-powered electricity plants[3], while also pursuing renewable energy sources [29].

Due to rich South African coal supplies, energy has historically been cheap [30]. This was particularly the case for electricity up until 2007. South Africa's electricity was ranked cheapest globally up until 2012 [31]. As a result, a high electrical energy dependency developed within industry as it was more cost effective to focus on efficiency in other areas. This benefited a significant segment of South Africa's industries aimed at extracting and primary processing of these raw materials. These processes include gold, platinum group metals, cement, steel, vanadium, copper and chrome production. Most of these processes are highly energy intensive, and their production in South Africa has benefited greatly from historically cheap energy.

Various factors have led to increases in energy costs, including Eskom's electricity prices that have increased rapidly since 2007. In 2016, the utility was awarded a 9.4% increase[4], a figure above the inflation rate. Figure 2 shows Eskom's annual tariff increases compared with the national inflation rate. These increases have exceeded inflation since 2003. In 2016, South Africa's electricity costs were 271% of the reference figure for 2000.

Most South African industries do not have effective energy management programmes in place. Energy management developed over a long period in Europe and other developed markets due to high energy costs. The low cost of energy in South Africa meant that energy management often carried insufficient fiscal benefit to receive attention [32]. Now, these industries have to implement hastily developed energy management plans to curb increasing operational costs.

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[2] Eskom Holdings Limited, "Eskom annual report", Eskom, Johannesburg, 2016.
[3] Department of Energy, "Government Gazette No. 40494", Pretoria, 2016.
[4] Pretorius, W., "Why Nersa granted Eskom 9.4% tariff hike", fin24.com , Pretoria, 2016.

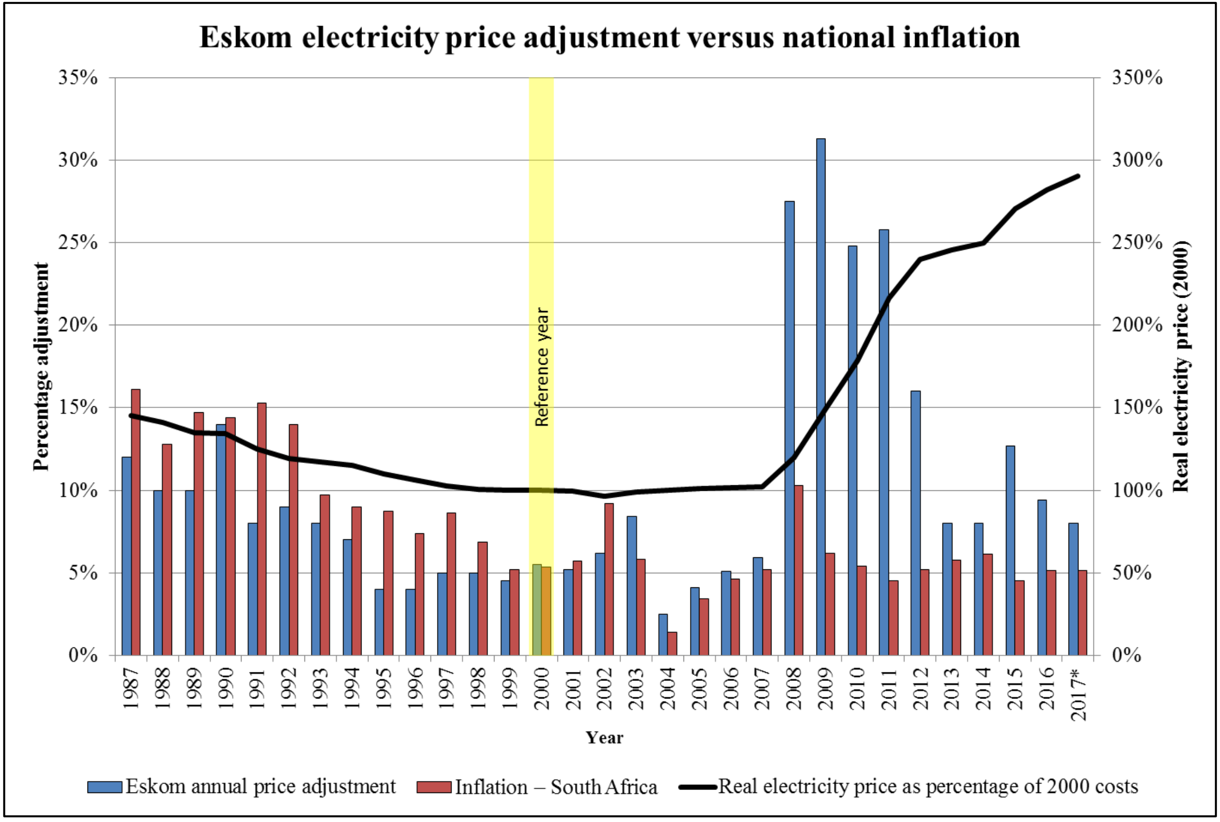

Figure 2: Eskom annual price increases for Megaflex tariffs versus South Africa's inflation rate [31] [5] [6]

A survey was conducted in South African industry to establish the number of personnel responsible for energy management. Table 1 shows the results. The number of employees responsible for energy was queried, as well as the type and number of production facilities. The results indicated that all companies have at least one responsible energy manager. However, the results also showed that most of these energy managers received support from personnel with other primary roles.

It can therefore be shown that South African industrial companies typically have very small energy management teams, with some teams as small as only one person. In many cases, the energy manager has never been appointed formally. These teams also often consist of people who have other primary duties (virtual energy management teams). Effectively, very little headway has been made in implementing energy management systems that achieve real results.

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[5] Eskom Holdings Limited, "Eskom annual report", Eskom, Johannesburg, 2016.

[6] Ramokgopa, B., "Tariff history," Eskom, Johannesburg, 2005.

Table 1: Survey of South African companies and energy managers[7] [8]

Industry	Company	Full-time energy managers	Energy team members with other primary responsibilities	Approximate annual energy cost	Comments
Gold mining and refining	GM Group 1	1	6	R1.8 billion	
	GM Group 2	2	4	R3.1 billion	
	GM Group 3	1	8	R1.8 billion	Energy manager also responsible for water
Steelmaking	SM Group 1	1	9	R6.0 billion	Energy manager first appointed in 2016
	SM Group 2	1	8	R3.2 billion	
Cement-making	CM Group 1	1	6	R0.5 billion	Energy manager at corporate level
	CM Group 2	1	4	R0.5 billion	Energy manager at corporate level

Besides being understaffed, energy management teams are often underfunded and do not have the technical expertise to achieve energy savings. The few personnel able to work on energy management do not have the time or the technical expertise to perform knowledge work.

Furthermore, energy management in industry is inherently complex [33]. Complex processes are difficult to understand and manage effectively. Additionally, having multiple energy carriers to manage adds layers of complexity. These personnel require a strategy to begin implementing basic energy management practices.

1.4 Energy management

1.4.1 Existing energy management strategies

Historically, energy has been treated as a fixed overhead cost. This was due to relatively cheap energy prices, which did not provide incentive for efficient energy use [33]. As this situation changed globally, effective energy use has become a more prominent concern. Many energy savings opportunities identified in industry are technology-replacement projects. Although these projects often make financial sense, the level of investment does not reflect this [23]. Access to

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[7] Table developed from interviews conducted with company personnel and provided energy accounts.

[8] Company and operation names will be kept anonymous to ensure confidentiality.

capital is a major barrier to these investments [34]. This problem is called the energy efficiency gap [35].

Research has shown that there are other energy opportunities available for implementing energy management practices [21]. This has resulted in energy management receiving increased attention since the energy crises that resulted from petroleum shortages in industrial countries in the 1970s. Work on a standard for energy management systems started with the publishing of IS 393 in Ireland. This was followed by the European energy management standard, EN16001, in 2009 [36]. ISO 50001 was published in 2011, which is expected to have a significant impact on global energy use [26].

ISO 50001 has been designed to be suitable for application in any organisation, independent of size. The standard identifies the requirements, such as policies, processes and commitments, for an effective energy management system. However, because ISO 50001 has been developed to be broadly applicable, it does not provide guidelines on industry-specific technical approaches [37], [38]. Figure 3 shows the basic structure of an ISO 50001-compliant energy management system.

ISO 50001 primarily provides guidelines on the policy and planning level. On the technical level, it only indicates what should be in place. For example, on energy measurement, ISO 50001 provides the following guidelines:

> "*The organization shall ensure that the key characteristics of its operations that determine energy performance are monitored, measured and analysed at planned intervals.*" [39]

ISO 50001 identifies five characteristics as the minimum requirements, namely:

- Significant energy uses,
- Variables affecting significant energy uses,
- Energy performance indicators,
- Effectiveness of energy plans, and
- Evaluation of expected versus actual energy consumption [39].

This guideline is most useful in hindsight, or with a system already in place. However, overwhelmed energy managers require a more tangible strategy for implementing the practical aspects of energy management. As Bunse *et al.* identified, "*to close the gap between theory and practice research should focus on developing efficient and effective energy management in production*." [36]. This statement reflects that there is a need for a practical strategy to implement effective energy management in industry.

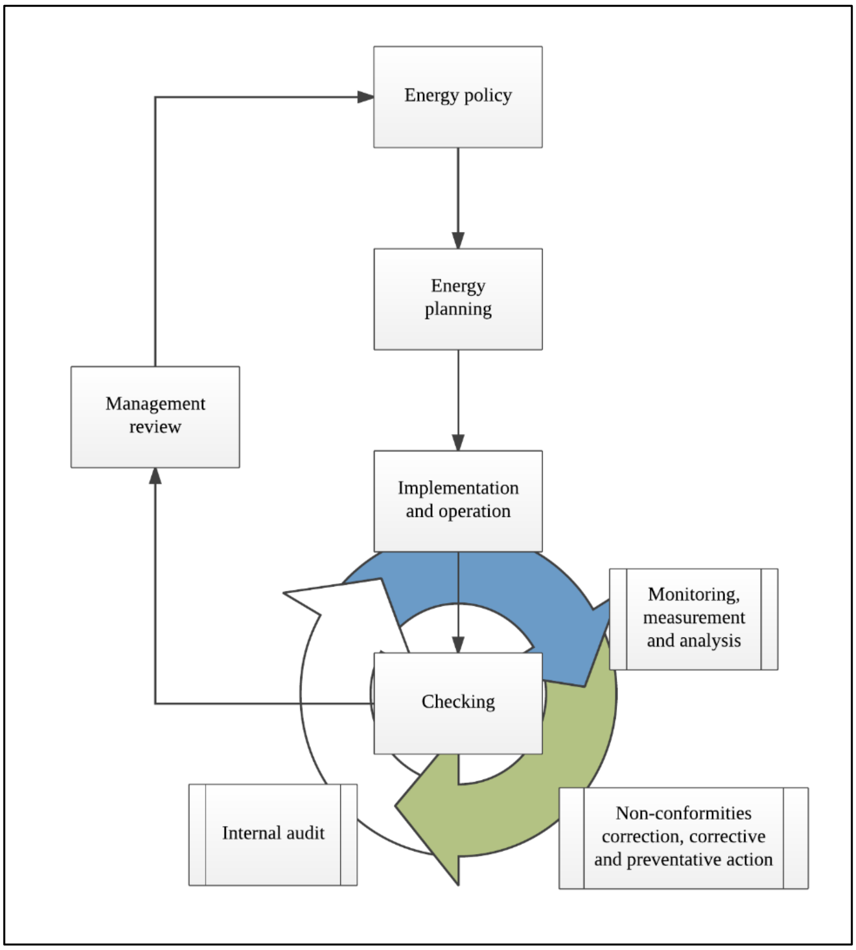

Figure 3: ISO 50001-compliant energy management system [39]

1.4.2 Operational energy management

Although industry is unwilling or often unable to invest in capital-intensive energy efficiency projects, some low cost activities can have a significant impact [40]. These savings require no or small capital investments with short payback periods. As such, industrial companies should be mandated to achieve these savings as part of their responsibility to shareholders and the environment.

Operational energy management is the accurate measurement, correct analysis and useful feedback of energy usage information, and can lead to improved performance. Unlike the activities traditionally associated with energy management [13], operational energy management does not involve replacing old technology with more efficient versions or changing processes. Instead, energy management consists of ensuring processes operate at or close to their maximum energy efficiency levels. Performance problems are identified and corrected quickly.

This form of energy management can also be linked to “monitoring and targeting” [41], “monitoring, targeting and reporting” [42] or implementing an energy management information system [16]. Research and case studies have shown potential energy consumption savings of 5% can be achieved through implementing operational energy management [16], [41], [43]. Maneschijn, Vosloo and Pelzer also showed through a case study that a R3.5 million per annum saving had been achieved by implementing energy feedback [44].

The principle of operational energy management is that it allows for the identification and arrest of deviations from optimal operating energy efficiency [45]. In most energy intensive processes, there are continual changes in energy consumption. Energy consumption can vary due to changes in the production process or the control boundaries, or due to poor management of the relevant process. In order to ensure that the process operates as efficiently as possible, energy consumption must be measured accurately, analysed correctly and feedback must be given to personnel empowered to act upon the information in a timely manner.

According to the Energy Technology Support Unit (ETSU), reduced energy waste and costs in business operations and information regarding performance and potential for improved performance are the principle drivers for implementing this type of energy management [41].

Operational energy management can therefore be seen as a subset of a good energy management system. Because these savings can be significant and are achieved at little to no cost, it forms a much quicker route to energy savings. This is illustrated in Figure 4.

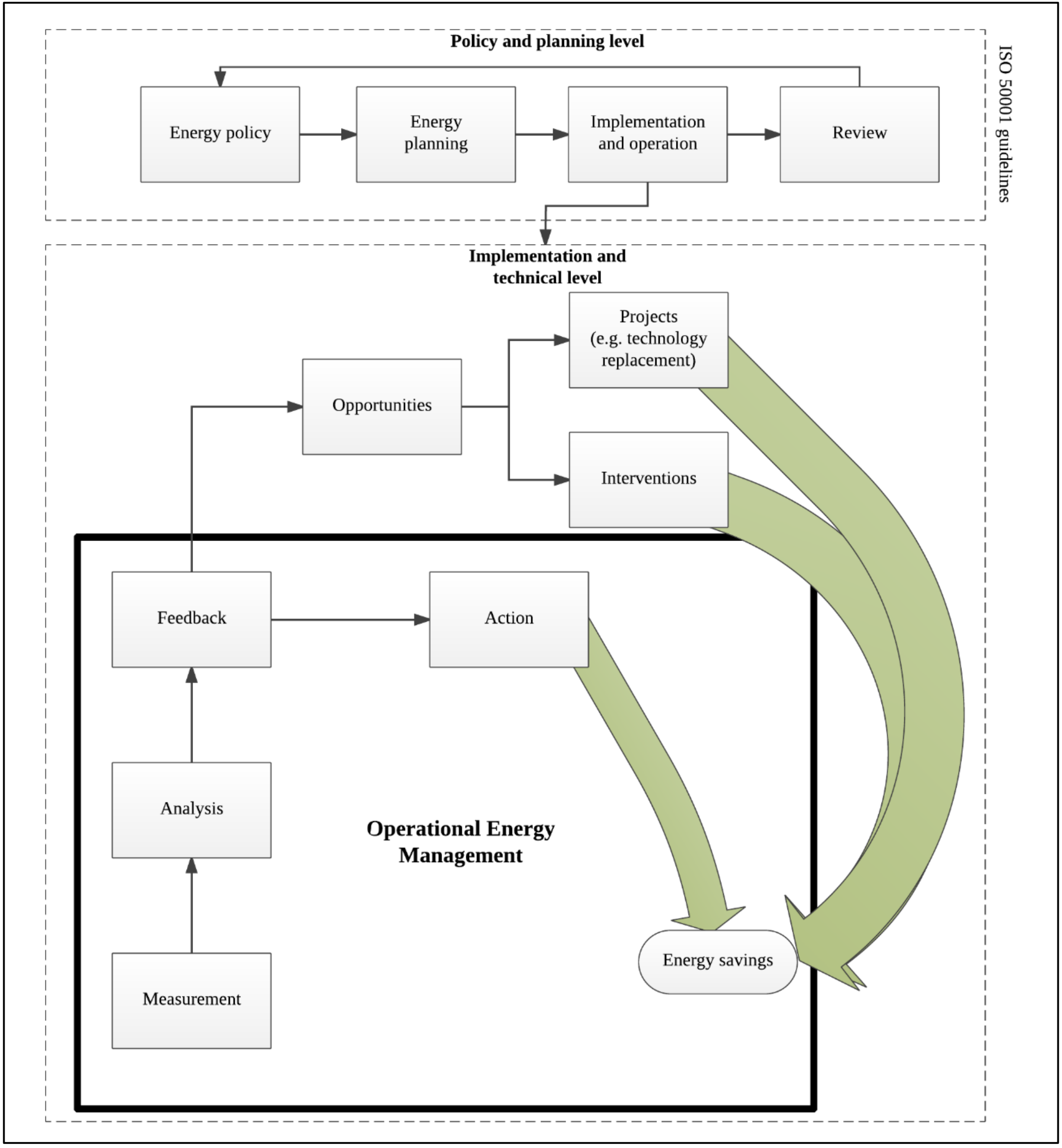

Figure 4: Operational energy management as a subset of an energy management system

There are several ways in which operational energy management can improve energy performance. Three examples will be briefly discussed, namely, reduced variability (outliers), reduced artificial inflation and improved efficiency.

Figure 5 shows an example of reducing outlying events. Typically, these events are mistakes made when established best practices are not followed. An example of this is auxiliary equipment not being shut down when a plant is not operational. By reducing these outlying non-conformities, the overall efficiency of the system is improved over time.

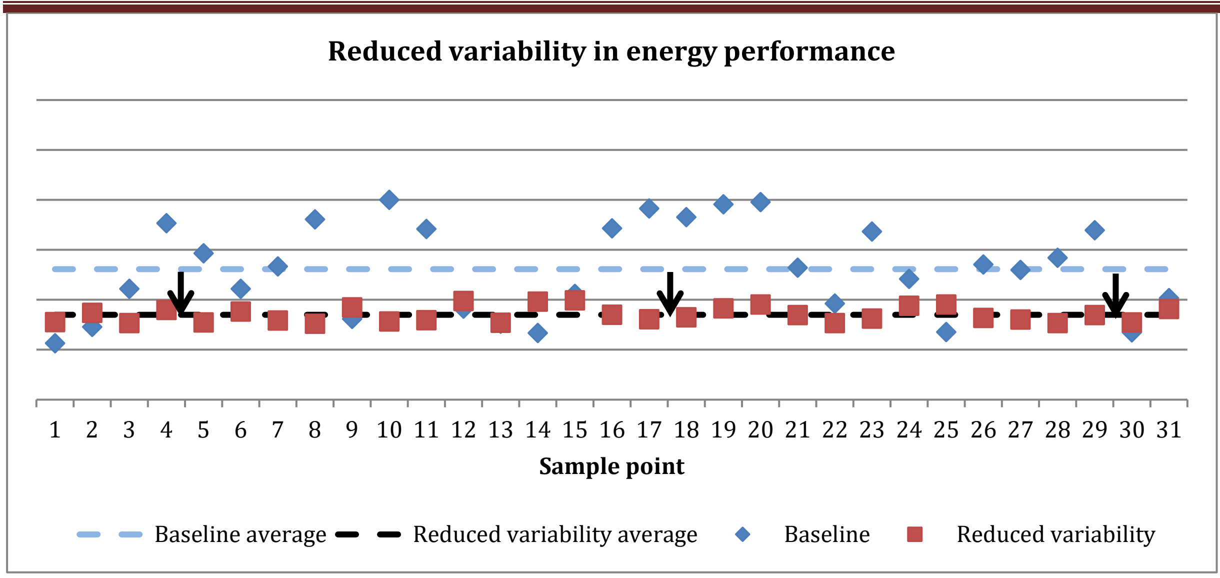

Figure 5: Example of improved energy performance through reduced variability

Figure 6 shows an example of reduced artificial inflation. Typically, a plant is designed to operate at a specified level of efficiency when built. However, as the plant is operated, operational inefficiencies cause the plant to drift away from this performance level. If not properly monitored and arrested, this artificial inflation is often built into the system targets for the following time periods – such as a budget being increased due to a plant not achieving its target. Operational energy management can also be used in this way to prevent the deterioration of performance in energy interventions [46].

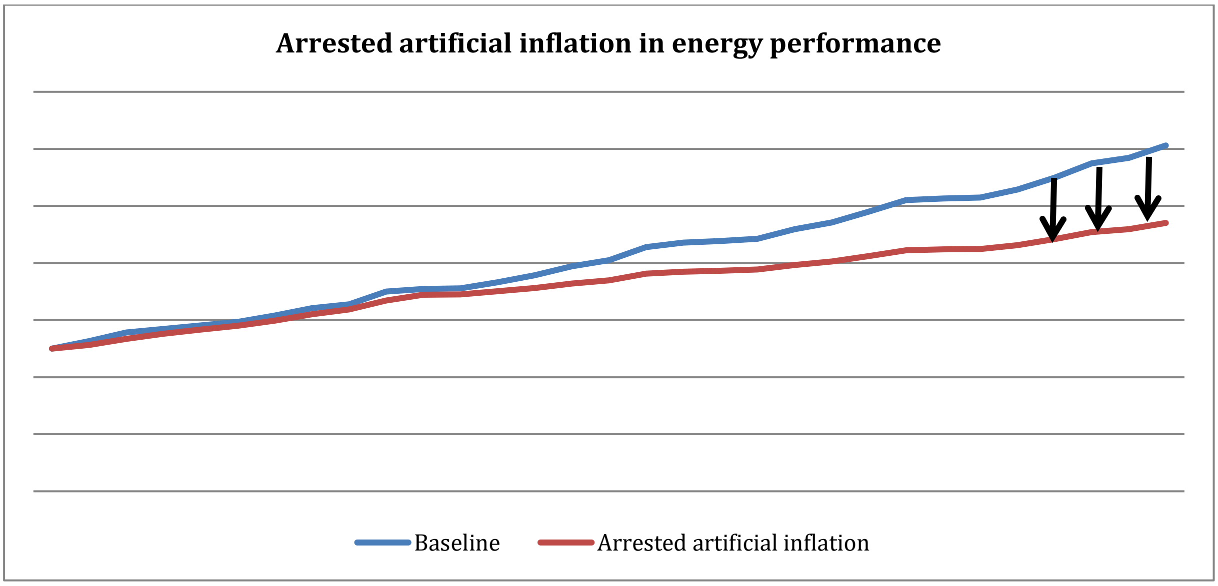

Figure 6: Example of improved energy performance by reducing artificial inflation

Improved energy performance is achieved by improving operational efficiency so that the system operates closer to a theoretical optimal point. Although this point cannot be achieved, setting it as a target reduces waste. An example of this is operating mills on a plant so that the throughput is at an optimal level, thus improving the plant's kWh/tonne performance. Figure 7 shows an example of improved operational efficiency.

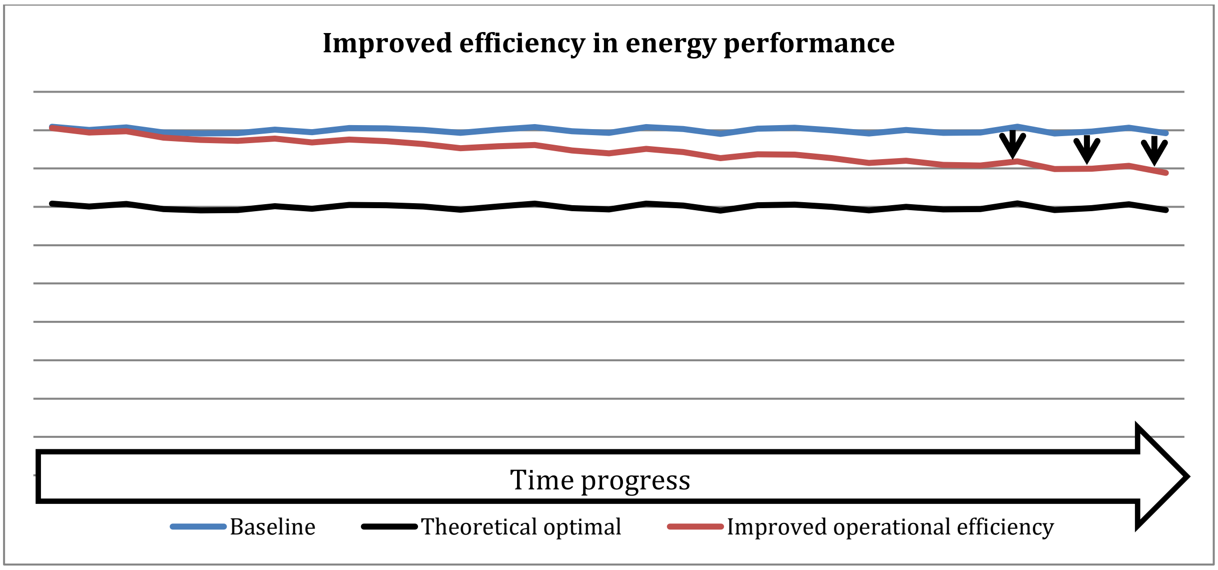

Figure 7: Example of improved energy performance through improved operational efficiency

Achieving these operational savings is not simple. Effective energy management is generally specific to industry [47] as well as to a particular situation. This makes it difficult for standards such as ISO 50001 to provide technical guidelines. Further, personnel managing significant energy users[9] (SEUs) are often tasked with multiple attention-consuming responsibilities, such as production, maintenance and safety. These more urgent concerns often leave no capacity for energy management considerations.

There are several requirements for operational energy management. The first is the availability of reliable, measured energy data. International research has shown that energy sub-metering is often not implemented [48]. This barrier can be difficult to overcome as no literature or guidance could

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[9] ISO 50001 refers to Significant Energy Uses rather than SEUs. In ISO 50001, this is defined as the manner or kind of application of a substantial amount of energy. It can therefore be seen in part as a more abstract view, whereas SEU refers to a specific system or installation that consumes energy. In this thesis, SEUs will be used to refer to significant energy using systems.

be found providing a strategy for energy metering. In South Africa, this is compounded by existing and upcoming legislature.

There are three factors that need to be considered regarding energy measurement. The first is the scope of the measurements, specifically what is measured and where. The second is the quality of measurements to ensure that measurements are accurate enough to be reliably acted upon. Third is the quality and availability of the data provided by these measurements. In many industries, energy data metering is of poor quality and insufficient scope. Even in cases where metering is sufficient, data is often located on isolated networks and not readily available for analysis.

The next requirement is data analysis. Industry does not properly understand what to do with the data that has been collected to lead to energy savings. In most cases, the data is reported as is with little to no processing or context added (data dump). Even in cases where data is being reported against targets, there is insufficient care given to understanding the root cause of non-conformities. Literature suggests using black-box models to analyse data [49]. This method does not encourage an understanding of underlying systems, leading to potential missed savings.

Finally, energy feedback is a significant problem. Industry does not know how to develop feedback on energy performance in such a way as to promote effective action. Typically, this is caused by all feedback being routed to a single person (the energy manager). It is also a symptom of a shotgun approach being taken to feedback – only a single form of feedback is provided and it must cater for all recipients equally. Another common problem is using a key performance indicator (KPI) system on its own as the only form of feedback. KPIs are presented as a single-figure evaluation of performance. While this can help identify problems, it does not identify the causes or facilitate corrective action.

To assist these personnel, best practices have been developed to improve energy management [47]. These best practices are static, meaning that personnel are introduced to them but few facilities have plans in place to ensure that they are carried out. Best practices are typically audited only once every few years, and are often not maintained properly during intermediate periods. As achieving these operational energy management savings is difficult unless they are monitored continually, an effective method of dynamic feedback is needed.

These barriers prevent energy savings through operational energy management. To overcome the three barriers, they must be addressed in turn by reviewing available literature and the prevailing circumstances in industry. For each step of the operational energy management process, a strategy must be formulated to overcome the barriers. These strategies must form part of an overall strategy to promote dynamic operational energy management in industry. This is shown in Figure 8.

Operational energy management, in the context of this thesis, will therefor relate to the following three key steps. The first part will deal with the measurement of energy use to a sufficient level of accuracy to provide reliable data. The second part will deal with the modelling and evaluation of a system's energy performance. The final part will relate to providing feedback regarding the measured and expected energy performance.

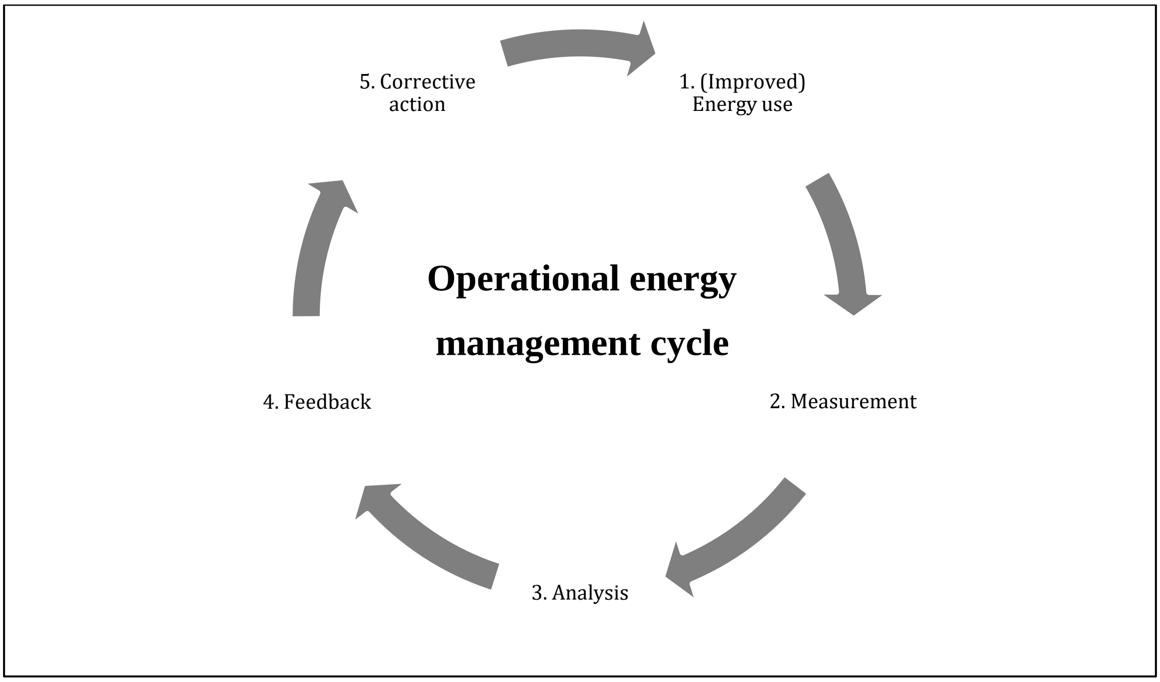


Figure 8: The operational energy management cycle

1.5 System-based approach

It has been proposed that improving energy efficiency should be done at system level because waste typically occurs in systems. This waste is commonly caused when parts of the system are operated inefficiently. For example, operating the motors of a mill while the mill is not processing materials for an extended period.

Many energy saving interventions have been implemented on South African industrial systems. Several case studies on mines have shown significant savings using a system-based approach. Vosloo, Liebenberg and Velleman [50] implemented an optimisation and control system on two gold mines, resulting in energy savings in one case, and energy cost savings on both mines. This was done by simulating and optimising the integrated water reticulation system of the mines. In another case study, Pelzer *et al.* [51] achieved load-shifting energy cost savings on four mine dewatering systems. In both these case studies, the savings could not have been achieved unless the entire system was considered. The savings relied on operating specific parts of the system (the pumps) so that dam water levels were managed and expensive energy costs avoided.

Energy savings were achieved by optimising compressed air systems in the gold mining [52] and platinum mining industries [53], [54]. On gold mine cooling systems, Du Plessis *et al.* [55] showed energy savings by taking a system-based approach. These interventions did not involve savings on individual components, but rather took a system-based approach to optimise the operation of the different components together.

Swanepoel *et al.* [56], and Maneschijn, Vosloo and Pelzer [57] showed energy cost savings on the raw milling systems of cement plants. This was achieved by operating cement grinding mills so that production occurred during times that electricity was cheapest. This could only be done due to the availability of storage capacity in the form of silos.

Industrial facilities can be arranged into logical levels from the entire facility down to individual machines. However, individual machines are grouped together in most facilities to perform a certain task. Typically, these systems are the lowest level where operator control is practised. Except for some very old plants, most parts in these systems are automated to work together, or are controlled from a central location.

By taking a system-based approach, energy-using systems can be measured, analysed and evaluated together. This study will therefore provide a framework for a system-based approach to operational energy management.

1.6 Need for study

There is a global need to use energy more efficiently [12]. Industry has been identified as having significant potential for efficiency improvements [13]–[15]. However, due to several barriers, uptake of energy efficient practices in industry has been slow [21]–[23]. In South Africa, small energy management teams together with historically cheap energy have resulted in energy management practices not being developed within industry [32]. However, with increasing energy costs, South African industry is increasingly in need of strategies to improve energy efficiency quickly and easily. A further problem is the significant economic strain on South African industries. This means that little investment capital is available for large energy efficiency projects.

One strategy to use energy more efficiently is to implement operational energy management, which literature shows can lead to savings of 5% [16], [41], [43]. While operational energy management does not require the significant initial capital investment required with technology-replacement projects, there are three significant barriers to its proper implementation.

Firstly, the reliability and effectiveness of existing energy metering is a problem as without energy data the strategy cannot be implemented. Secondly, an effective way to analyse the data is necessary as ineffective analysis will not allow action to be taken. Finally, feedback must be provided to the correct personnel to that ensure operational energy use is managed.

No single strategy could be found in literature that provides a sufficiently detailed framework for implementing operational energy management. This study will solve the general problem of improving energy efficiency in industry. Specifically, this study will provide a framework for implementing operational energy management.

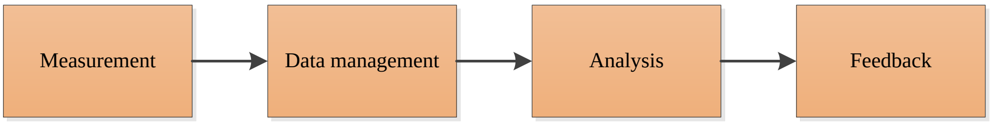
1.7 Contributions of study

1.7.1 Overview

This study will provide multiple contributions in the form of a principal contribution and several component contributions. The principal contribution of this study will be a comprehensive methodology for operational energy management. The three component contributions will each relate to a different part of the operational energy management process, namely, measurement, analysis and feedback.

1.7.2 Principal contribution

A new system-based strategy for integrated operational energy management



Problem

South African industry is struggling to remain competitive while managing escalating energy and operational costs. Currently, industry faces several barriers to finance large energy saving projects. Implementing operational energy management has the potential to provide 5% energy savings [16], [41], [43]. Overloaded and unsuitably qualified energy managers require a strategy for practically implementing operational energy management in a way that is integrated, sustainable and will produce energy savings.

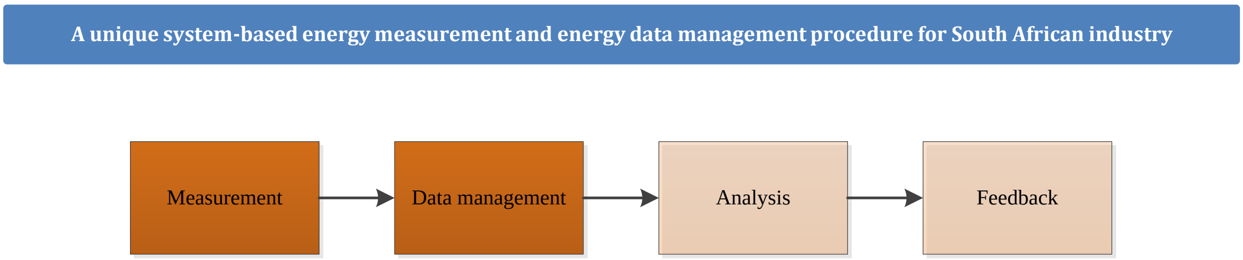
Limitations of existing research

Several guidelines provide an overview of operational energy management [16], [41], [42]. These guidelines identify energy measurement, analysis and feedback as the primary steps of operational energy management. The primary limitation of existing research is the lack of detail. While many guidelines identify the overarching concepts of operational energy management, they do not facilitate the implementation thereof. This is because the standards rely on the expertise of the energy manager to develop a framework for operational energy management. Due to their large number of responsibilities and inexperience with energy management systems, energy managers in South Africa are unable to develop and implement a framework for energy management without significant assistance.

Contribution of this study

This thesis will provide a system-based strategy for integrated operational energy management. The state of the art of the components of operational energy management, namely, measurement, analysis and feedback, will be determined. From this, an integrated strategy will be developed, providing a methodology for measurement, analysis and feedback. To improve the ease of implementation as well as encourage decentralisation of operational energy management, a system-based approach will be developed.

1.7.3 Component contribution 1



Problem

The maxim "you cannot manage what you cannot measure" holds true for energy management [58]. Without energy consumption information, it is not possible to determine the state of energy performance. Energy measurement in industry is especially complex as there are often multiple energy carriers at a facility. In many cases, these energy carriers are not measured effectively, or are measured incorrectly [41]. This is especially true where the energy content cannot be measured directly (such as coal).

Further, in many facilities, energy measurement data is often unreliable and not available where needed for energy management. This is due to metering devices that are located on data islands, or not connected at all. In effect, these measurement devices cannot be used effectively for operational energy management.

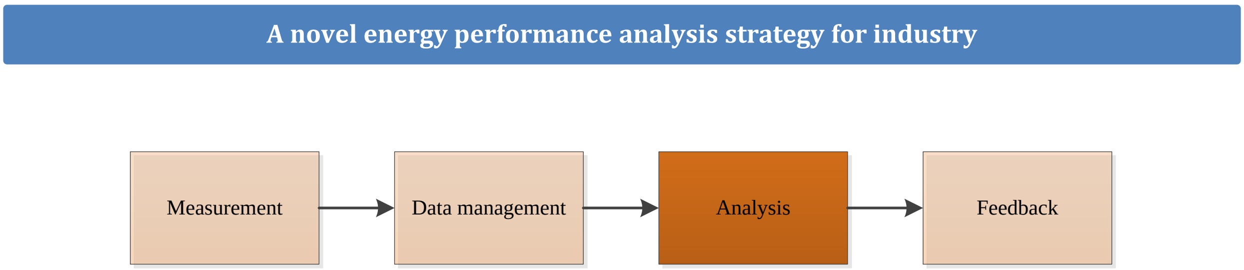
Limitations of existing research

Several non-comprehensive energy measurement strategies are available in literature [16], [42]. These strategies typically focus purely on electricity consumption [59], [60], while many South African industries additionally use coal, natural gas and other energy carriers. Few studies focus on metering quality, and not in the context of operational energy management [61], [62]. Further, existing strategies are often vague and rely heavily on the experience of responsible personnel to choose effective metering locations. Many industrial facilities also have their own strategies for deciding how to measure energy, as will be discussed in Chapter 2. Further, little research could be found regarding energy data measurement, with the exception of the residential sector [63] and a single case study in a brewery [64]. Literature that adequately addressed the problems described earlier in this section could not be found.

Contribution of this study

In this thesis, a new strategy for energy measurement and data management will be developed. This strategy will incorporate energy measurement scope: where meters should be located; and energy measurement quality: what should be measured and how. The strategy will also provide a framework for energy measurement data management, ensuring that the data is available when and where it will be most effective for operational energy management. This combined strategy will provide the first and foundational step of operational energy management: reliable energy measurement data.

1.7.4 Component contribution 2



Problem

The analysis phase has been identified as a key weakness in underperforming operational energy management systems [41]. In most South African industries, very little is in place to provide context for energy data. Energy managers are often faced with a data dump, with significant work needed to understand the data. Without this further analysis, energy measurement data has very little use in supporting energy management [42]. Where a target or a budget for energy is provided, it is often developed in such a way as to provide a wholly unrealistic view of energy consumption. In order to provide an accurate view of energy performance, the energy data must be analysed in a way that will identify wastages and will allow personnel to act to reduce these wastages.

Limitations of existing research

Existing strategies in industry for determining energy performance have several shortcomings. Foremost is a lack of understanding of the underlying energy drivers when indicators are determined. Existing indicators are typically used purely for accounting and tracking purposes, and not to give direction for improvement. These indicators are typically not useful in determining the root cause of any changes. They are therefore not suited to the purpose of improving dynamic awareness of energy.

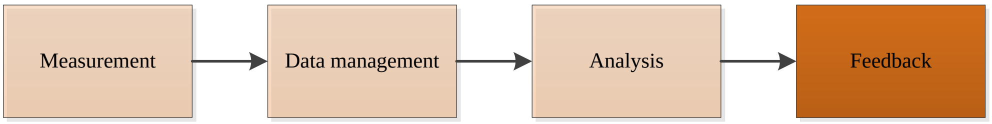
Most literature provides either insufficient detail [16], [42] or only graphical and aggregate techniques for operational energy management, as will be discussed in more detail in Chapter 2. Several techniques are presented [37], [49], [65], but no integrated strategy could be found in literature. As a result, there is generally a gap between the tools available, and the ability to implement them [36]. Further, many of the existing tools assume that perfect data availability and modelling are possible, and do not provide an effective strategy for dealing with real-world scenarios.

Contribution of this study

This study will provide a process for implementing effective analysis of energy data in industry to determine energy performance. A systematic process for identifying energy drivers acting on systems will be provided. Important energy driver information will be identified. Following this, a unique method for energy data analysis will be presented, and a framework for the application of the method will be provided. Two analysis methods will be developed. The first is based on the available literature, whilst the second will be uniquely developed for South African industry. This framework will allow for the second phase of effective operational energy management, which is analysis, to be put in place.

1.7.5 Component contribution 3

A novel strategy for sustainable operational energy management through integration and effective feedback



Problem

In most of South African industry, energy management activities are performed by a small number of appointed individuals. These individuals are often not part of the operational process, and as a result often have difficulty in exercising control over energy users [41]. Personnel responsible for operational efficiency must therefore be incorporated into the strategy.

However, these personnel often have other, more pressing responsibilities, such as production and safety. Operational personnel are typically not enabled to monitor, act on or improve energy performance due to a lack of effective energy feedback. Most feedback employed by South African industry is focused on aggregate information, which does not assist in making decisions that will improve energy performance.

Prior work has also shown that the marginalisation of energy management, such as by viewing it as the responsibility of only a select department, is a key cause of energy management failing to be effective [37]. Instead, an integrated management system is necessary.

Limitations of existing research

Energy management standards support the notion that energy management should be everyone's responsibility. However, standards such as ISO 50001 [39] focus primarily on doing this through awareness campaigns. The standard also recommends involving personnel responsible for SEUs. Existing standards and guidelines do not provide an effective framework or strategy for effectively ensuring responsibility for energy consumers.

Existing methodologies available in literature address only individual parts of energy feedback [41], [42], [44]. Other research only provides some considerations without effectively stating how these considerations must be implemented [43], [47], [66]–[70]. There is no single, synthesized framework for energy feedback available in literature.

Contribution of this study

This study will provide a new strategy for implementing system-based feedback. A systematic process for identifying stakeholders will be developed, ensuring that feedback is comprehensive. Important factors for consideration for feedback, along with criteria, will be identified. The methodology will present a guideline for ensuring that feedback is effective. By implementing this strategy, operational personnel will be enabled to improve energy performance, thereby supporting operational energy management.

1.8 Outline of thesis

1.8.1 Chapter 1

In this chapter, the problems surrounding industrial energy consumption were introduced and discussed. Operational energy management was presented as a solution to this problem, but several barriers were identified preventing such a strategy from being implemented. A new strategy was proposed for South African industry, and the components and objectives of this novel strategy were developed and discussed.

1.8.2 Chapter 2

In Chapter 2, an in-depth review of the literature regarding of operational energy management is conducted. Practices relevant to operational energy management that already exist in South African industry are evaluated. Following this, a detailed literature review is conducted. Through this review, the state and requirements for an operational energy management system is identified.

1.8.3 Chapter 3

In Chapter 3, a methodology is developed based on the criteria identified in Chapter 2. This methodology is developed in three parts, namely, measurement, analysis and feedback. The developed methodology is presented and a verification test is conducted to show that the methodology meets the requirements identified in Chapter 2.

1.8.4 Chapter 4

In Chapter 4, the implementation of the developed methodology in South African industry is shown. The methodology is applied to a South African gold mining group. The verification of measurement devices, implementation of a data management system, implementation of analysis and feedback is shown.

1.8.5 Chapter 5

In Chapter 5, the developed methodology is validated through case studies of South African industry. Results are provided for the implementation discussed in Chapter 4, showing the savings achieved by implementing the methodology. Several additional examples are used to illustrate the specific mechanisms through which operational energy management facilitate energy savings.

1.8.6 Chapter 6

Chapter 6 summarises and concludes this thesis. The results of the energy management strategy are discussed and evaluated, allowing for a useful conclusion regarding the success of the study to be evaluated. Finally, the shortfalls of this study are discussed and recommendations made for further research.

Chapter 2 Operational energy management concepts and literature

2.1 Preamble

In this chapter, an overview of the concepts pertinent to the study not detailed in Chapter 1 will be provided. This will include some of the key concepts of operational energy management. Following this, the three primary steps for operational energy management, namely, measurement, analysis and feedback, will be discussed in detail.

For each step of the process, a review of available academic literature is conducted. In this review, the contributions and shortfalls of the literature are identified. Next, some of the methods through which the step is currently implemented in industry are provided. From this combined overview, the needs can be identified for the methodology to be developed in Chapter 3.

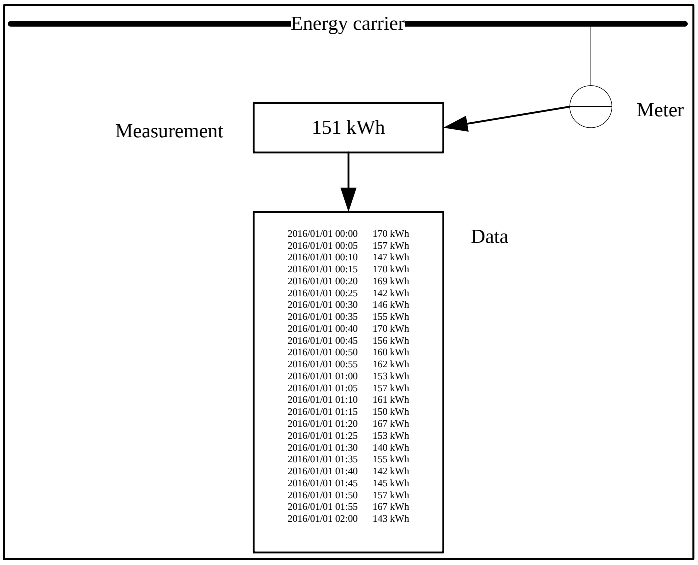
2.2 Accurate measurement of energy use

2.2.1 Overview

Measurement is a foundational step in all forms of energy management [71]. Adequate energy sub-metering is also required to comply with the ISO 50001 standard [39]. Without access to reliable energy usage data, it is impossible to quantify productive energy consumption or energy wastage. In industry, any investment of time, attention or capital into energy savings also requires that the potential return on this investment is determined. Without measurement, this analysis cannot be done.

It is important to understand what is meant by meters, measurements, data and metering. Figure 9 illustrates an example of each. A meter is a physical device capable of measuring a quality of the energy carrier in question. A measurement is a single instance of reading the meter. Multiple readings and information such as the time at which the reading was taken constitute data.

For operational energy management, the focus of analysis is on energy-using systems. As such, metering energy usage of these systems is the goal. Most industries have some form of metering in place, which may or may not be suitable for operational energy management. In other industries, only basic check metering is in place, and significant work must be done before operational energy management can be implemented.



2016/01/01 00:00	170 kWh
2016/01/01 00:05	157 kWh
2016/01/01 00:10	147 kWh
2016/01/01 00:15	170 kWh
2016/01/01 00:20	169 kWh
2016/01/01 00:25	142 kWh
2016/01/01 00:30	146 kWh
2016/01/01 00:35	155 kWh
2016/01/01 00:40	170 kWh
2016/01/01 00:45	156 kWh
2016/01/01 00:50	160 kWh
2016/01/01 00:55	162 kWh
2016/01/01 01:00	153 kWh
2016/01/01 01:05	157 kWh
2016/01/01 01:10	161 kWh
2016/01/01 01:15	150 kWh
2016/01/01 01:20	167 kWh
2016/01/01 01:25	153 kWh
2016/01/01 01:30	140 kWh
2016/01/01 01:35	155 kWh
2016/01/01 01:40	142 kWh
2016/01/01 01:45	145 kWh
2016/01/01 01:50	157 kWh
2016/01/01 01:55	167 kWh
2016/01/01 02:00	143 kWh

Figure 9: Examples of meters, measurements and data

Three components of metering will be discussed, namely, quality, scope and data. Metering scope concerns deciding what should be metered and where. As energy carriers are transported, stored and consumed throughout industrial plants, there are multiple locations where they can be metered. Some carriers are metered at point of use, while others are metered by the utility provider before they are transferred to the plant.

The two concerns of metering quality are the accuracy of the measurement, and the qualities that are measured. Increasing levels of accuracy can be costly, but inaccurate metering will yield results that cannot be used. Further, the energy content of many energy carriers such as coal used in plants cannot be measured directly. In these cases, measurements such as weight of volume are used in conjunction with ancillary data sources.

The third component that will be discussed is data. With the advancement of digital technology, modern meters have become more practical. It has become cost effective to link energy meters to a computer network so that energy data is available automatically and in real time. However, in many cases, meters are linked to isolated networks. The data is often not available where it is needed to facilitate operational energy management.

This section will therefore focus on addressing these three concepts in metering.

2.2.2 Review of metering in industry and literature

Metering scope

Energy use on industrial sites can be very complex. Most of these sites have multiple SEUs, multiple energy carriers, and processes that convert energy for specific purposes. For electricity, there are usually multiple points of delivery for a single facility and multiple distribution routes. Coal is delivered by truck or railway, and is often stored in silos, bunkers or stockpiles. Natural gas may be supplied through a single or multiple points.

Other energy carriers used in industry that must be considered include off-gases, steam, compressed air and chilled water. These are typically generated on-site through energy intensive processes. Some industrial plants also cogenerate electricity on-site. A synopsis of the different energy carriers used in industry is shown in Table 2.

Table 2: Energy carriers typically found in South African industry

Industry	Company	Typical primary energy carriers	Typical energy carriers generated on-site
Gold mining and refining	GM Group 1	Electricity	Compressed air, chilled water, cogenerated electricity
	GM Group 2	Electricity	Compressed air, chilled water, cogenerated electricity
	GM Group 3	Electricity, coal	Compressed air, chilled water, cogenerated electricity
Platinum mining and smelting	PM Group 1	Electricity	Compressed air, chilled water
	PM Group 2	Electricity	Compressed air, chilled water
	PM Group 3	Electricity	Compressed air, chilled water
Steelmaking	SM Group 1	Coal, electricity, natural gas	Process off-gases, compressed air, steam, cogenerated electricity
	SM Group 2	Coal, electricity, natural gas	Process off-gases, compressed air, steam, cogenerated electricity
Cement-making	CM Group 1	Coal, electricity	Compressed air
	CM Group 2	Coal, electricity	

Due to the large number of energy carriers employed on industrial facilities and their widespread use, the energy carrier network of an industrial facility can be difficult to analyse. A systematic approach is required to ensure that the network is understood comprehensively.

ISO 50001 provides no guidelines regarding energy measurement, but does provide a list of minimum requirements. The standard calls for the monitoring, measurement and analysis at planned intervals of significant energy uses, relevant variables to these uses, energy performance indicators and actual energy consumption compared with expected [72]. In the context of measurement, this means ensuring that the scope of energy measurement includes all significant energy uses.

Literature regarding energy metering for energy management purposes is sparse. Textbooks [73], guides [16], [42] and studies [59], [60] on the subject do not provide comprehensive strategies for establishing energy metering.

A course on Industrial Energy Management made available by South Africa's Department of Energy [42] touches on the subject of energy metering. This module recommends cataloguing available data sources before deciding whether supplementary systems are necessary. It does not offer a strategy on implementing such an exercise, but does provide the following criteria to consider:

- Acceptable levels of uncertainty – As measuring all variables or measuring any variable to 100% accuracy may be prohibitively expensive, is it important to understand the level of certainty that is required.
- Cost of implementation – As measurement devices and peripherals have associated costs, the total cost of metering cannot be disproportionate to the potential benefit.
- Complexity of energy use variables – The influencing factors as well as their relationship to energy use, also typically called energy drivers. For example, ambient temperature is an energy driver of air-conditioning. In certain cases, some factors may be safely assumed to be constant and do not need to be measured.
- Number of energy savings measures to be monitored.

This work is generally of insufficient detail and only provides a few additional points to consider when establishing metering.

Hooke, Landry and Hart [16] provide a more detailed consideration to energy metering. As a strategy for deciding on where to locate meters, a four-step process is proposed:

- Step 1: Review existing site plans.

- Step 2: Develop a list of existing meters.
- Step 3: Assign energy accountability centres according to the facility's business layout.
- Step 4: Decide on additional metering by following a systematic approach.

Hooke *et al.* [16] does not discuss the recommended systematic approach in any further detail. This process does not consider the information already available to assist in decision-making. For example, a list of installed electric motors can provide an indication of where SEUs are located. Using this information, large consumers with more capacity for improvement can be targeted.

Hooke *et al.* recommended additional meters based on the number of existing meters in energy accountability centres. This may cause overmetering of small energy users and undermetering of SEUs. Although both the scope and the quality of measurements are discussed, this work does not provide a comprehensive strategy for deciding on metering locations.

Few studies have been published regarding metering locations. O'Driscoll and O'Donnell [60] published a state-of-the-art review of industrial power and energy metering in 2003. This study identifies resolution, sampling rate and accuracy as considerations for electricity meters. While the review discusses technical aspects of electrical meters, it does not provide a strategy for metering locations. This study is also limited to electrical metering only.

In a case study, O'Driscoll, Cusack and O'Donnell [59] discuss the implementation of electricity meters at a biomedical facility. In this study, the authors propose installing temporary meters at the main incomer, all distribution boards and SEUs. These can then be replaced by permanent meters later. This strategy is not practical for large industrial facilities with many of these points. In these cases, an impractically large number of meters may be necessary, and the installation and removal process will be very time-consuming, leading to missed savings opportunities. This strategy also does not consider other energy carriers.

Vikhorev, Greenough and Brown state that "*the most significant energy consumers … need to be identified, monitored and analysed in real time to increase industrial energy efficiency*" [58]. Through this statement, the authors effectively indicate that a systematic approach is needed when approaching energy management. This work also highlights the importance of targeting SEUs.

Kara, Bogdanski and Li [74] provide a framework for electricity metering specific to manufacturing. Their approach divides metering into factory, department and unit levels, and is particularly suited for compliance and accounting purposes. Further, one of the aims of this work is to identify the technical qualities of measurement devices and the situations to which they are suited. This highly comprehensive approach is suitable where energy metering is already in place, or electricity prices are disproportionately high. However, in South Africa, the cost of such comprehensive metering may be prohibitive and counterproductive. Further, this methodology does not support other energy carriers.

Thiede, Posselt and Herrmann [75] provide a simplified methodology for determining whether meters are required for specific equipment specifically for small and medium enterprises. This approach differentiates between SEUs and small energy consumers, as well as whether equipment has highly variable or constant energy demands. In certain cases, the authors propose that only a single measurement is taken, and that energy consumption be modelled based on other factors.

This approach is suitable for small enterprises, but several limitations and problems make it unsuitable for industry. The most fundamental problem with this approach is that operational energy management specifically deals with non-conforming energy use towards modelled behaviour. Checking the model against itself will not identify energy wastage.

The available literature is summarised in Table 3, which shows the contributions and limitations of previous works. From this, the requirements for measurement scope can be established. In the next section, existing methodologies found in some South African industries will be reviewed.

In industry, a simple methodology is to compare the energy consumption of systems and allocate additional meters to the largest consumer. Figure 10 shows an example of this methodology. In the figure, the different sub-systems of a South African gold mine have been arranged as per their contribution to total energy consumption. In this case, the methodology typically employed would advocate for implementing the next available meters on the compressed air sub-system.

Table 3: Summary of literature regarding energy measurement scope

Authors	Contributions	Limitations
ISO [72]	Requirement: Measurement of significant energy uses.	Does not provide a guideline for meeting requirements.
Department of Energy [42]	Considerations: Accuracy, cost of metering, complexity of measurement.	Does not provide a strategy for implementing measurement.
Hooke *et al.* [16]	Four-step process for establishing additional metering.	Proposed process does not incorporate available information. Does not provide detail on proposed "systematic process".
O'Driscoll and O'Donnell [60]	Considerations: Accuracy, resolution, sampling rate.	Electricity only. Does not provide a strategy for implementing measurement.
O'Driscoll *et al.* [59]	Case study, basic methodology for metering strategy.	Electricity only. Proposed strategy not suitable for heavy industry.
Vikhorev *et al.* [58]	Identify need for systematic approach.	Does not provide a strategy for implementing measurement.
Kara *et al.* [74]	Electricity metering methodology for manufacturing industry.	Electricity only. Must be adapted for heavy industry.
Thiede *et al.* [75]	Simplified energy measurement methodology for small and medium enterprises.	Approach cannot be directly scaled to energy intensive industry.

This methodology does not provide guidance where no existing metering is in place. Further, it also does not provide adequate criteria as to whether additional meters are required. Instead, it provides a simple means of determining where further metering can be utilised. There are several potential problems to this methodology. This method does not consider that large energy consumption may be due to wastage, thereby attributing additional metering to a system which may not require it. Some systems also require far more metering devices to sub-meter, compared to others. This is usually the case where the system has distributed energy users or a large number of small motors. For example, on many gold mines, underground mining is a large consumer, but this consumption is due to a large number of small users. Metering each small user will be very expensive and may not yield sufficient results to cover the costs. Another failure of this methodology is that it is primarily aimed at electricity use, and does not consider other types of energy carrier. It also does not consider transmission losses, and does not provide a method for deciding between equally sized systems.

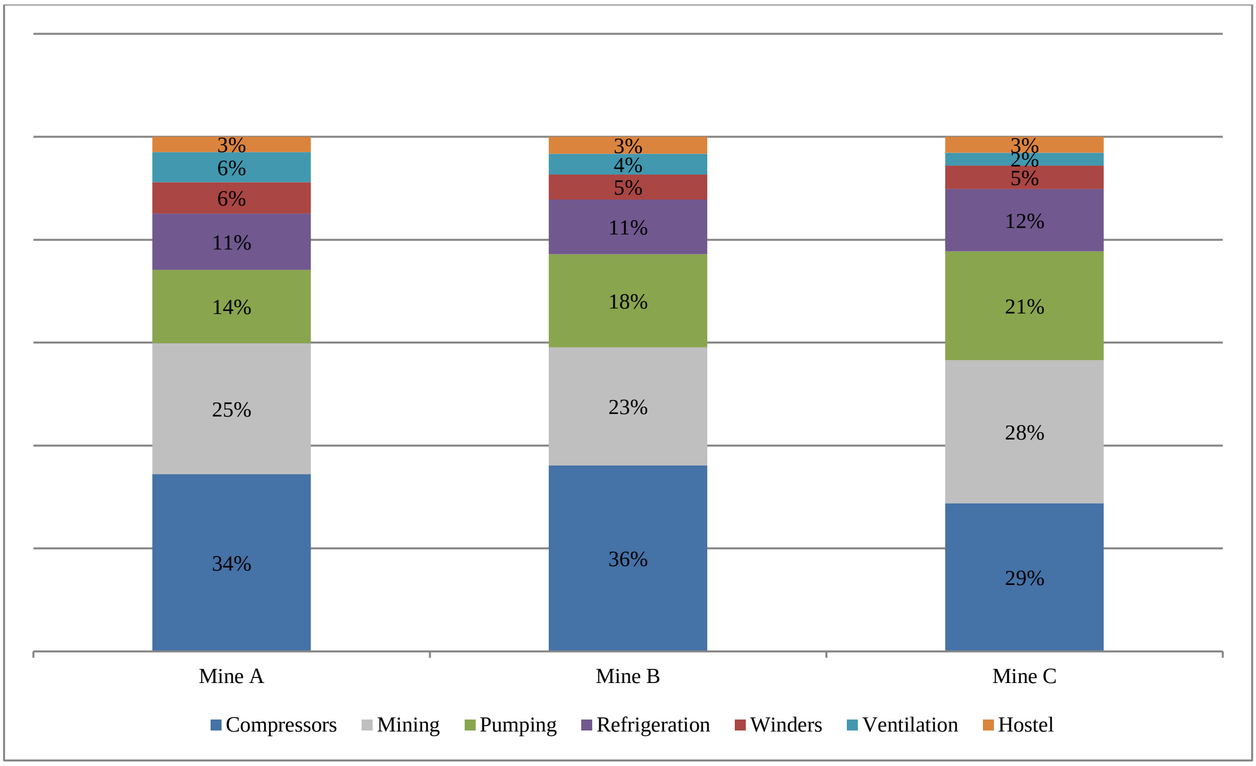


Figure 10: Relative energy consumption of different mine sub-systems

Metering quality

Industry typically employs various types of energy carrier. While the energy content in some carriers such as electricity is easy to measure, others require sampling and analysis. In the case of electricity, energy transported is measured directly. This means that no ancillary measurement is necessary. Although measuring power quality is an important consideration in industry, it will not be discussed in this document.

In South Africa, 92% of electricity is generated using coal for thermal energy [76]. Coal is also used for both thermal energy and chemical constituents in steelmaking and cement. Typically, coal use is measured in tonnes. As coal energy content can vary widely, further analysis is required. For example, in South Africa, coal calorific values have been shown to differ from 25 MJ/kg to 31 MJ/kg [61].

Coal is typically sold by weight in tonnes. A part of many delivery contracts is for suppliers to perform coal quality analyses at an accredited facility. The issued certificate is supplied with the coal delivery. These certificates, in addition to chemical composition, also indicate energy content.

On many South African industrial plants, laboratories analyse coal supplies, again determining energy content.

Industry in South Africa also burns natural gas to supply thermal energy. Gas makes up approximately 3% of the primary energy supply [76]. The steel, pulp and paper, and food and beverage industries consume gas for energy. Some industries also produce off-gases from certain processes, such as coke-making [77]. These gases are also extensively used for thermal energy.

Gas is measured in volume, such as cubic metres. Suppliers typically invoice clients for energy content sold, in terms of rand per gigajoule. In some industries, devices capable of measuring the Wobbe index of the gas are used. These devices perform an online analysis of the gas to determine the energy content per unit of volume. An important consideration for measuring gas is the calibration of metering equipment [16]. As the volume of the gas changes depending on the temperature and pressure of the distribution network, an unsuited or uncalibrated metering device will return incorrect readings.

A common issue found in industry is that the energy content of combustible fuels is assumed to remain constant. The performance of the plant is compared year-on-year while only the volume of the energy carrier is considered. This leads to inaccurate performance results. For example, utilising higher quality coal that provides more thermal energy per weight measure will lead to an appearance of improved energy efficiency. Van Niekerk, Vosloo and Mathews [61] show that this can lead to faults of up to 10% in energy consumption statistics.

Compressed air is used extensively in the mining and steelmaking industries. In some cases, it is used on cement plants as well. Compressed air is typically generated using electricity, though in some cases, steam turbines are used instead. Compressed air is typically measured in volumetric flow. The potential energy of the compressed air correlates with the pressure.

Chilled water is also used in the mining industry to provide cooling underground. It is typically measured in volume. Cooling ability is measured in the temperature of the water.

Finally, steam is used in several industries. It is a necessary step in electricity generation in South Africa. It is also used in the steel industry to drive certain turbines for heating applications and for cleaning. Steam is measured in tonnes. The relevant ancillary qualities are temperature and pressure. Table 4 summarises several energy carriers as well as the ancillary measurements typically required.

Table 4: Quantity and ancillary measurements for energy carriers used in industry

Energy carrier	Quantity measurement	Ancillary measurement
Electricity	Kilowatt-hour	–
Coal	Weight measurement – tonnes	Composite analysis, test certificate
Gas	Volume measurement – standard cubic metres	Wobbe analyser, invoice
Compressed air	Volume measurement – standard cubic metres	Pressure measurement
Chilled water	Volume measurement – litres	Temperature measurement
Steam	Weight measurement – tonnes	Temperature and pressure measurement

Vijayaraghavan and Dornfeld [66] identify a prime consideration for industrial energy metering, namely, the method of taking measurements. The two options identified are manual and automated measurements. In this context, a manual measurement means a device that continually takes measurements but does not record them. A measurement from such a device is only available if a worker travels to the device and records the reading. The reading is only available for that specific time. An automated device typically has a built-in storage facility. These devices take measurements continually and record data, such as the time of the measurement. This does not necessarily mean that the device is connected to a communication network, as will be discussed in later in this section.

As technology improved, automated measurement devices have become far more economically feasible. However, some plants still use manual measurements. This should be avoided in an energy intensive industry as it can be impossibly cumbersome in a complex system [66]. Manual readings can typically not be taken at a sufficient frequency for effective energy management. They require extensive manpower; without appropriate information technology support systems this can lead to reading or typographical errors. It is recommended that an automated digital metering system be used as far as it is economically feasible.

Deciding on measurement accuracy is simplified by reviewing existing and upcoming South African legislature. Relevant existing legislature is South Africa’s section 12L tax incentive, which was promulgated in November 2013. This incentive can provide a significant benefit where energy efficiency initiatives have been implemented. However, the strict data and information compliance needed makes claiming incentives a complex problem [62].

Additionally, South Africa's Minister of Energy has published draft regulations on compulsory reporting of energy data to the government [78]. These regulations were originally aimed to commence in March 2012, and are set to come into effect as soon as public comment has been reviewed. A requirement of the regulations is for industry to ensure that the data provided is accurate.

South African National Standards 50010:2011 (SANS 50010) form part of the requirements for both section 12L and energy reporting. It can therefore be used to provide a guideline for measurement accuracy. SANS 50010 is a South African standard for the measurement and verification of energy savings. This standards is relatively strict, requiring the use of traceable and calibrated measurements.

In an application in the industrial demand side management (DSM) sector, Meijsen, Van Rensburg and Booysen [79] show the importance of, and provide a method for, verifying metering devices. In this work, the most common causes of electricity metering problems are identified. The authors propose a method for verifying meters using a checking device.

A summary of relevant literature is provided in Table 5. Based on the literature review, it can be determined that measurement quality that is compliant with SANS 50010 will be sufficient and assist with legislative compliance.

Table 5: Summary of literature regarding energy measurement quality

Authors	Contributions	Limitations
ISO [72]	Requirement: Measurement of relevant variables.	Does not provide a guideline for meeting requirements.
Van Niekerk *et al.* [61]	Considerations: Energy content must be quantified due to high variance.	Research not directed towards energy management.
Vijayaraghavan and Dornfeld [66]	Considerations: Manual measurements are not suited in industry. Measurements should be automated where feasible.	Does not provide a strategy for implementing measurement.
National Treasury [80]	Requirement: Compliance with SANS 50010 for measurement.	Requirements only.
Department of Energy [78]	Requirement: Compliance with SANS 50010 for measurement.	Requirements only.
Meijsen *et al.* [79]	Considerations: Verification of measurement devices.	Electricity only.

Energy data management

For the purpose of operational energy management, energy is measured to allow for analysis and feedback. As will be discussed in sections 2.3 and 2.4, this requires that the measured data be accessible and available in a timely manner. Because of this, data management is an important consideration.

There are several scenarios prevalent in South African industry that cause problems with implementing operational energy management. These include:

- Measurement devices that must be read manually,
- Measurement devices on data islands, and
- Data islands on networks that are not accessible.

There are still cases of some measurement devices that must be read manually. This requires personnel to travel to the device, record the reading and capture the data manually to an accounting system. Fortunately, most of these devices are being phased out as there are several problems with performing operational energy management with this data type:

- A single measurement is retrieved once per month or week, resulting in a very low data resolution.
- Human error can cause incorrect readings.

Because of this, it is recommended that these devices be replaced if they are associated with energy streams that carry a high value. The second problem is with measurement devices that are isolated on data islands, meaning that they have limited connectivity. There are two common scenarios. The first scenario is meters that record data, but that are not connected to a data communication network. In this case, a user must retrieve the data manually from the device – usually on a weekly or monthly basis. While this data may be useful for analysis, the delay between measurement and availability for use means that this data cannot be used effectively for operational energy management.

The second scenario is a set of measurement devices that record data and transfer it to a data storage server, where the entire data network is isolated. This is often found where individual departments in industry have installed their own energy metering devices. An example of this type of network is shown in Figure 11. In these cases, the energy data, although available in real time, may not be accessible at all the points where it is required.

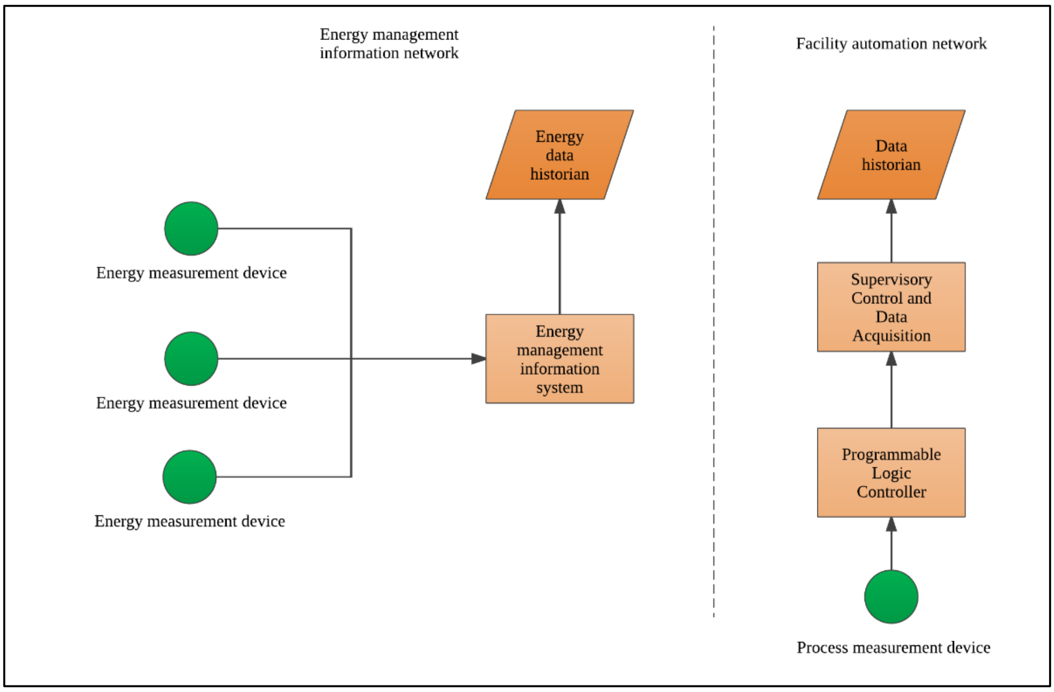


Figure 11: Isolated energy data metering networks

Another problem is when energy data is not available on the same network as energy driver data. This is often the case as energy metering systems are implemented in parallel with process control. In these cases, a bridge is required between the two networks to allow access. It is critical that the systems responsible for analysis and feedback have access to both sets of data to ensure operational energy management can take place.

Prior work on energy management data is scarce. Early work on the subject came well before data communication to metering devices was feasible. In these works, energy meter readings are collected manually [64]. More recently, Ueno *et al.* [63] demonstrate the effectiveness of instantaneous communication between meters and databases in the residential sector.

Vikhorev *et al.* [58] state that an organisation-wide data standard should be developed for all energy carriers to promote improved energy efficiency. However, this work does not provide further guidance on developing such a standard. The authors do however indicate that this standard should identify the sampling periods, data precision, as well as metadata required.

Vijayaraghavan and Dornfeld [66] identify the temporal scale as a consideration. This scale shows that different types of energy decision are made at different levels within an organisation. For each level, information is required for a different time period. Taken further, it can be inferred that some data may be required in near real time, while other data will only be required at scheduled intervals. This concept is shown graphically in Figure 12.

Hooke *et al.* [16] provide several reasons why real-time data is required. Firstly, they indicate real-time data will provide feedback quickly enough for action to be taken when performance deteriorates. Secondly, high resolution data is more suitable for understanding the behaviour of a system and for modelling using the data (as will be discussed in Section 2.3). Additionally, other process data is available in real time, and the authors believe that energy data should also be real time so that it is included in process performance management.

Although this recommendation is suitable for certain scenarios, there is a lack of differentiation when deciding whether measurement data is required in real-time. For example, coal is typically measured in terms of daily tonnes and energy content analysis is done periodically. Attempting to achieve exact real-time feedback would be prohibitively expensive. However, in the spirit of this recommendation, quantities can be monitored and analysed.

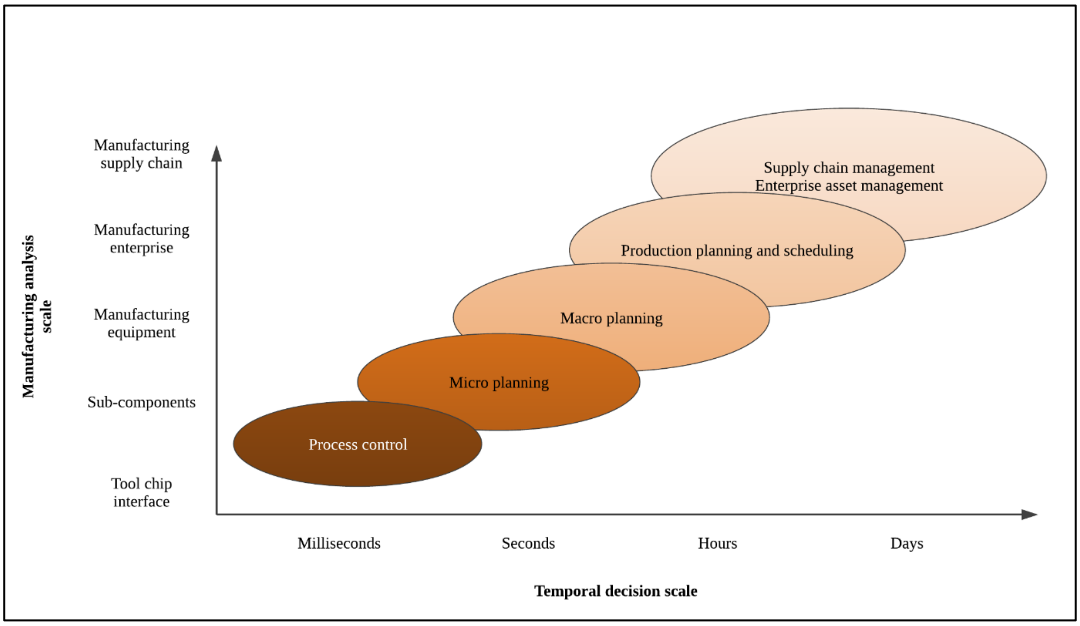


Figure 12: Temporal scale of decision-making in manufacturing (adapted from [66])

A related problem often found in industry is the resolution of available data. For example, in South Africa, Eskom measures electricity demand in half-hourly intervals. Facilities have an agreed upon notified maximum demand (NMD), which is a half-hourly demand that may not be exceeded or penalties may apply. However, certain energy management information systems do not facilitate monitoring energy consumption in finer resolution than half-hourly. As such, it is impossible to use this system to monitor actual demand compared with NMD. Thus, it is important that energy data is available in a suitable resolution.

Data integrity must also be considered for operational energy management. This is due to technical or human errors causing inaccurate or incorrect data to be reported. As operational energy management is susceptible to the problem of "garbage in, garbage out", this can lead to problems further in the process.

In highly relevant work in South African industry, Du Plessis, Pelzer and Kleingeld identify several common data integrity problems found when implementing and maintaining DSM projects [81]. Typical problems in this field are identified as data corruption, and partial or complete data loss. In other work, Du Plessis states that it is important to identify such data problems rather than ignoring them as this will result in incorrect information further downstream [82]. In this specific instance, this work refers to incorrect information about the performance of DSM projects.

There are many potential causes of incorrect data being reported. The measurement device might go out of calibration due to physical disturbances, or break down completely. Certain cumulative meters have a maximum value that can be recorded. Once this maximum is reached, the meter resets back to a reading of zero, which may be recorded as a negative reading. An electronic communication network between the measurement device and the data collection device may break down or receive interference. Human error in recording the data may lead to inaccurate data being recorded.

In industry, such disturbances are common and faults may go undetected for a long period. In some cases, the faulty readings are not detected and reporting goes on as before. As a result, the integrity of all further calculations and reporting done can be questioned. To avoid this potential scenario, it is therefore necessary to put simple checks in place to detect problems with data integrity.

A summary of the contributions and shortfalls of literature regarding energy data management is provided in Table 6. From this table, the requirements and considerations for energy data management can be established.

Table 6: Summary of literature regarding energy data management

Authors	Contributions	Limitations
Ueno *et al.* [63]	Considerations: Speed of communication between measurement device and feedback mechanism.	Research in residential and commercial sector. Energy use is relatively simple compared with industrial sector.
Vikhorev *et al.* [58]	Requirement: Standardised energy data.	Does not provide methodology for developing or implementing standard.
Vijayaraghavan and Dornfeld [66]	Considerations: Temporal data requirements.	Does not provide methodology for developing or implementing standard.
Hooke *et al.* [16]	Recommendation: Real-time feedback of measurements.	Recommendation only. Does not provide strategy of method for evaluating or implementing proposal.
Du Plessis *et al.* [81]	Identifies common data integrity problems.	Information only.
Du Plessis [82]	Requirement: Processes for managing data problems.	Requirement only.

2.3 Useful analysis of energy data

2.3.1 Overview

Analysis is the second step in the operational energy management process. The importance of effective analysis must not be understated. The purpose of analysis in this context is to evaluate the energy performance of a system reliably and realistically. This evaluation serves to identify when energy performance does not match intended levels. Where possible, analysis should also identify the cause of the non-conformance, and what corrective actions can be taken.

Energy managers in South African industry have a very large scope to their portfolios. Typically, there is only one energy manager per site, whilst in mining there may be only one energy manager for the entire mining group. These energy managers face the mammoth task of gathering, interpreting and acting on the data from 70 or more energy-consuming systems.

Because of this, it is crucial that energy data from the various systems be analysed effectively. Preferably, this analysis should take place automatically in an energy information management system. The purpose of this analysis is to reduce the data processing load on personnel whilst still informing them of any situation that requires further investigation and analysis.

Establishing a method for effective analysis can be intimidating as it requires a significant investment of time and effort. However, this initial investment makes it far easier to identify non-conformities and their potential causes during normal operations. Personnel in industrial companies often have multiple attention-consuming tasks with little capacity remaining for analysing and identifying inefficient systems. Therefore, effective analysis makes it far more likely that these personnel will be able to act on non-conforming systems.

Analysis has two primary considerations. The first is understanding the factors that influence energy use, allowing the user to model the system’s energy consumption characteristics effectively. The second is using this model, along with actual and forecast information to predict future energy use. This prediction has multiple uses. For operational energy management, the prediction can be compared with actual energy use to determine the system’s energy performance. Poor performance and its causes can be quickly identified and corrected.

Energy usage characteristics in industry

Most industrial processes have multiple production stages; in some cases with buffers between the different stages. The entire facility or plant is designed to convert resources into an end product through multiple processes working in synergy. Each process typically has multiple stages as well as supporting processes. Each stage or process is referred to as a s*ystem*. The individual systems have components, which are typically the plant's SEUs and supporting equipment. Figure 13 illustrates this concept.

Although energy consumption takes place at the component level, it is important to understand the vertical and horizontal interaction. Energy drivers typically act on the system level. Additionally, components usually act synergistically within a system. Depending on the role that each component plays in the system as a whole, the type of energy demand it places on the system may vary.

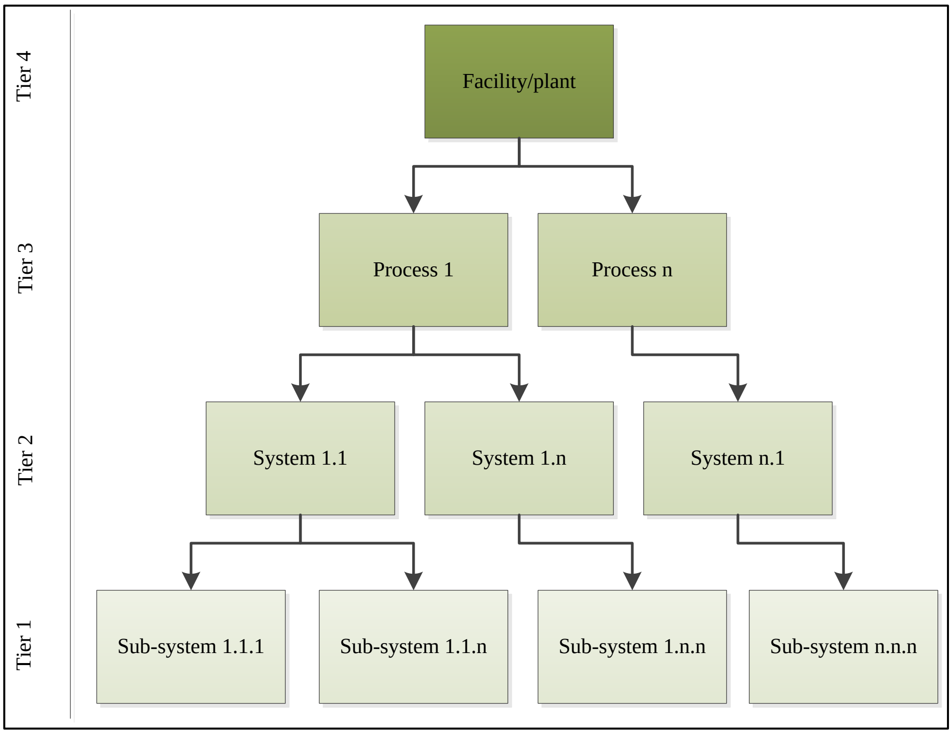


Figure 13: Graphic illustration of vertical integration of processes into a single facility or plant

Figure 14 shows an example of an energy usage profile typically found in an industrial system. All uses should have an energy driver. However, for ease of calculation and determination, a base energy usage is typically identified. This base use typically consists of multiple users with different energy drivers. However, these drivers are constant or very nearly constant. Thus, they are grouped together as a base energy use. This base is nearly always present in the system. However, the base is still important to understand as there is significant potential for energy savings when plants are shut down for longer periods of time. An example of this is a heating furnace on a steel plant, which must be maintained at 700 °C to 900 °C, even if no production is taking place.

The second category is operational auxiliary use. This is typically associated with auxiliary equipment operating in tandem with primary production equipment. This usage is typically present when the system is at an operational level. It often does not scale with production, but may have other energy drivers. An example of this is the motor lubricant pump of a mill.

The next category is a variable energy driver use. This use can generally be linked to a system's primary energy driver by an equation. Finally, there is a category termed "unattributed use". This usage varies, but cannot be attributed to any known energy driver. This load may or may not be present in the system at a given time. This use is typically a symptom of an energy-using system that is not fully understood.

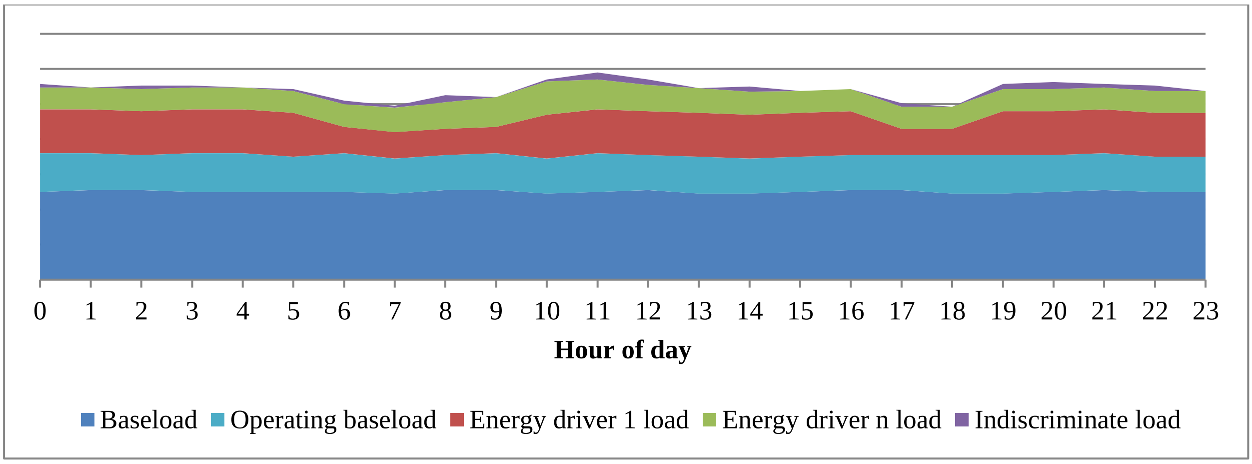


Figure 14: Example of hourly energy consumption of a system

It should be noted that all loads have a related energy driver. For analysis purposes, it is easier to group certain loads together as baseloads and others as unattributed use. However, as the energy management of the system improves, the energy manager should strive to identify and model the energy drivers for the un-attributable energy consumption as well. This should be done to ensure that all loads present on the system are in fact necessary, planned and managed.

Energy baseline, budgets and targets

Energy baselines, budgets and targets are all elements used in energy management, although each has its own specific purpose. They will be discussed in this section.

A baseline is a measurement of energy consumption typically used as a starting point before some form of intervention is implemented [39]. The baseline establishes existing energy usage and characterises it. The baseline can be scaled according to some scaling factor [83]. This is necessary as energy consumption often changes based on changes in operating conditions, such as increased production or increased mine depth; this is called a routine adjustment [84]. The baseline is used to predict what energy consumption would have been had the intervention not been implemented. By calculating the difference between the energy consumption after the intervention and the baseline, the impact of the intervention can be estimated [85].

Establishing a baseline is often an initial step in the process of beginning an energy efficiency drive, as without one it is impossible to determine whether there has been actual improvement. An effective baseline can help management determine the return on investment (ROI) of initiatives. This helps management determine where the ROI is high enough to continue interventions and projects, and where money is being wasted on ineffectual interventions.

Figure 15 shows an example of baseline usage. In the first year, the blue line on the left of the graph shows a baseline being measured as the actual energy consumption of that year. In the project performance year, the green line on the right of the graph represents the baseline. The red line on the right of the graph shows the actual energy consumption. The area between the green and red lines, marked with black arrows, shows the reduced energy consumption as a result of the project.

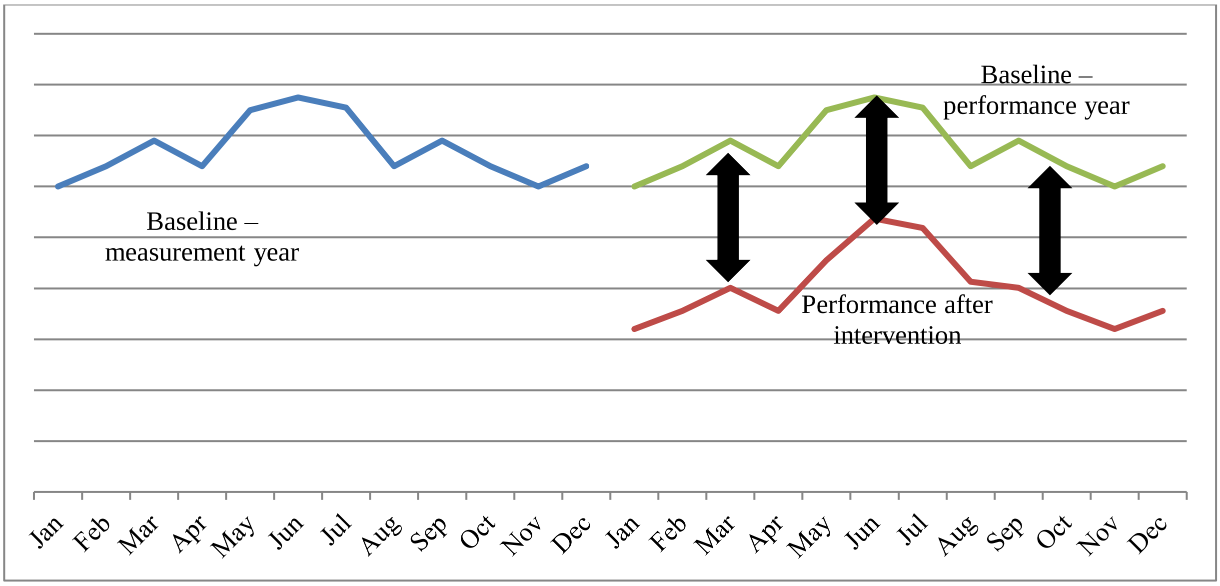


Figure 15: Baseline and actual performance used to determine energy savings

An energy budget can sometimes be mistaken for a baseline as many industrial energy consumers use baselines to budget for energy expenditure. This typically occurs when a more accurate estimation of energy consumption cannot be done, and operating conditions are expected to remain largely the same.

Energy budgets have been shown to be important in the cement and mining industries in South Africa [86]. An energy budget is typically developed to aid the financial department in estimating the company's expenditures for the coming year. With many industrial companies in South Africa spending more than R2 billion per annum on energy costs, accurate budgeting is critical. An inaccurate budget could lead to large cost overruns that negatively impact the company's financial position.

These energy budgets are communicated to operational departments to motivate them to use energy sensibly and to reduce wastage [87]. However, due to poor budgeting techniques, this is often ineffective. In an ideal situation, the energy budget can be considered a maximum demarcation for energy expenditures.

The energy budgeting process has an additional positive effect if applied correctly. By striving to accurately budget the energy needs for each system, it improves the understanding of each system's energy drivers. By understanding the mechanisms that drive the energy use for systems, the effectiveness of the system can be determined.

An energy budget also allows the energy manager to quickly determine which systems are performing poorly. Should a sudden change to the effectiveness of a system occur, the change in performance against the budget will assist energy managers in determining when an inefficiency has developed.

Finally, an effective energy budget has a very important role to play in the operations of an industrial facility. Having effective and timely feedback regarding the energy budget allows operators and the production team to determine when energy targets are not being met and react accordingly [88]. By reacting in time, activities that are unnecessarily wasting energy can be arrested or corrected.

Most budgeting methodologies currently employed in South African industry reflect an outdated way of thinking about energy costs, i.e. that of an unmanageable overhead. Energy budgets are determined using historical data multiplied by a factor to account for growth/shrinkage of the operation [88]. The cause of energy consumption is neither investigated nor understood, meaning that energy is not managed.

The energy target is typically set by company policy or legal legislature [72]. For example, in 2009 South Africa brought into effect the Power Conservation Programme, which required all electricity users to reduce consumption by 10% of baseline levels. This target is set as the goal for company energy consumption, and is usually based on the baseline or expenditures. An energy target is often set as part of an energy reduction drive.

An example of an energy budget and energy target is shown in Figure 16. In this example, the red line at the top shows the energy consumption that has been budgeted for. The green line at the bottom indicates energy consumption target levels. The black line in the middle indicates that performance started the year closer to the budget level, but approached the target level as the year progressed and interventions took place.

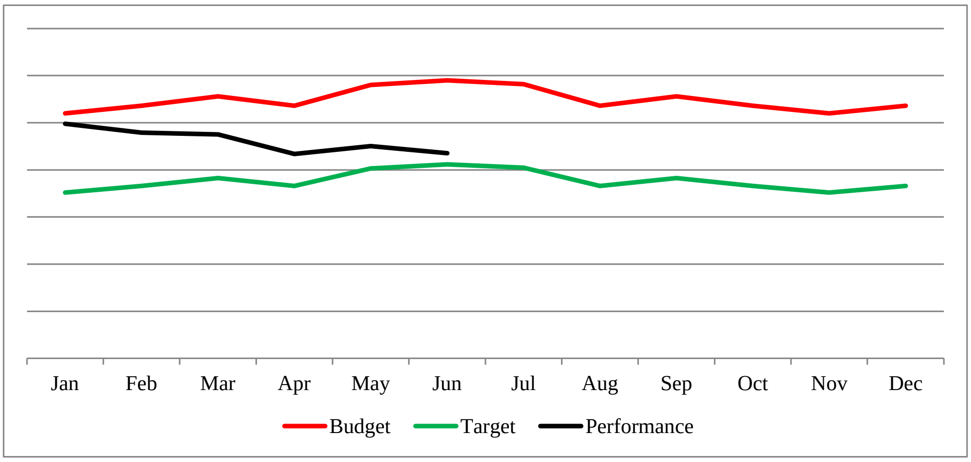


Figure 16: Energy budget and target versus actual performance

2.3.2 Existing performance measurement strategies

Existing methodologies applied in industry

Most South African industries already have budgeting methodologies as part of financial practice. One common methodology is to make a monthly estimate based on historical data along with assumptions. Typically, the implementation of such a budget can be expressed as in Equation (1).

$$E_m^{y+1} = F \cdot E_m^y + C \tag{1}$$

Where:

E_m^y is the sum of the energy consumed in the month *m* of the historical year *y*.

F is a multiplication factor estimating a nett increase or decrease in energy consumption.

C is a constant factor added or subtracted to address additional energy-consuming equipment being added to the system, or energy savings projects being implemented.

Other facilities use a baseload plus a correlation with production to estimate energy usage, as shown in Equation 2.

$$E_m^{y+1} = \frac{Pe_m^{y+1}}{P_m^y} \cdot E_m^y + C \tag{2}$$

Where:

Pe_m^{y+1} is an estimate production total for the month under consideration.

P_m^y is a historical production total.

All other symbols have the same meaning as in Equation (1).

Most existing budgeting methodologies follow a process of estimating monthly production totals. In some cases where load follows a pattern, historical profiles are used to subdivide this budget into intervals with sufficient resolution. For example, when purchasing electricity, Eskom measures electricity purchases in half-hourly intervals.

There are many shortfalls in existing budgeting methodologies. Foremost is the shortfall in accuracy. In many cases, existing budgeting methodologies can vary up to 7.73% from predicted [86].

Inaccurate budgets have many negative effects, of which the financial impact of unexpected high energy costs is just one [86]. Another significant problem is that an inaccurate budget can numb operational personnel to energy management. Because the budget target is set at an unrealistically low level, personnel are not motivated to even attempt reaching the target. Furthermore, unrealistically high budget targets do not promote any improvement in energy management.

A further problem comes with a lack of resolution. In order to effectively act to arrest or correct energy-wasting activities, personnel must receive feedback on the activity as quickly as possible. If the budget only exists at the monthly level, feedback is often only available on a monthly, or in some cases, an allocated weekly time frame [86], [88]. This feedback comes too late to have an impact, and often does not facilitate future improvements either.

The method by which the budgets for systems are determined is also typically poor. In most cases, all the systems are considered to support the primary production activity at the site. As such, an increase or decrease in production leads to a corresponding increase or decrease in energy budget. This method does not consider the actual relationship between the system and the production activities on-site. There are also instances where energy budgets are estimated at a facility and simply allocated to systems using past usage proportions.

Therefore, the largest flaw in existing methodologies is that they do not promote an understanding of the use of energy by plants, processes and systems [88]. This method often leads to complacency regarding energy management – the use of energy on a plant appears to be a “black box”, with energy going in for reasons that are not understood. Only through proper investigation and understanding can energy leaks and wastages be identified.

Figure 17 shows this process. In A, energy carriers feed into a process and production feeds out. Energy waste occurring within the production process cannot be identified without proper understanding of the energy usage. In B, properly identifying the usage of energy allows wastage to be identified. The actual energy usage and mechanics that require this energy usage is the energy driver, which must be understood for proper energy management.

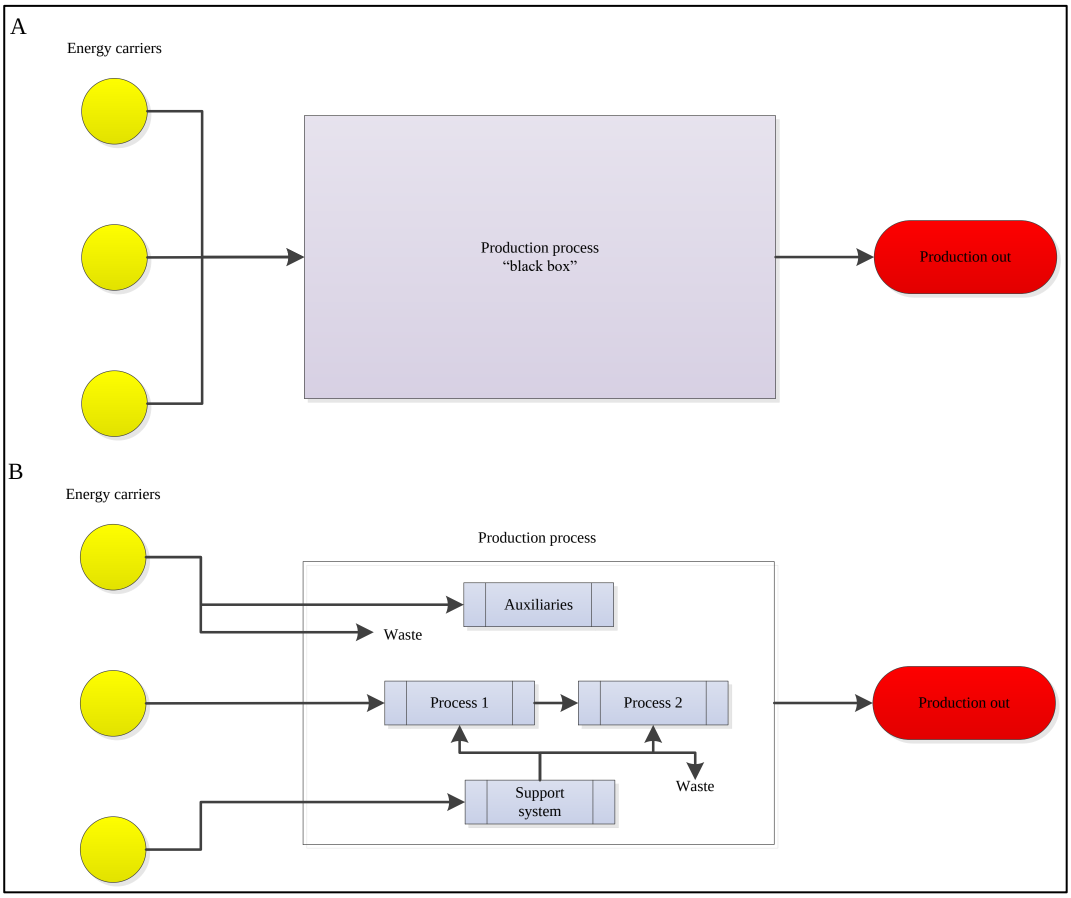
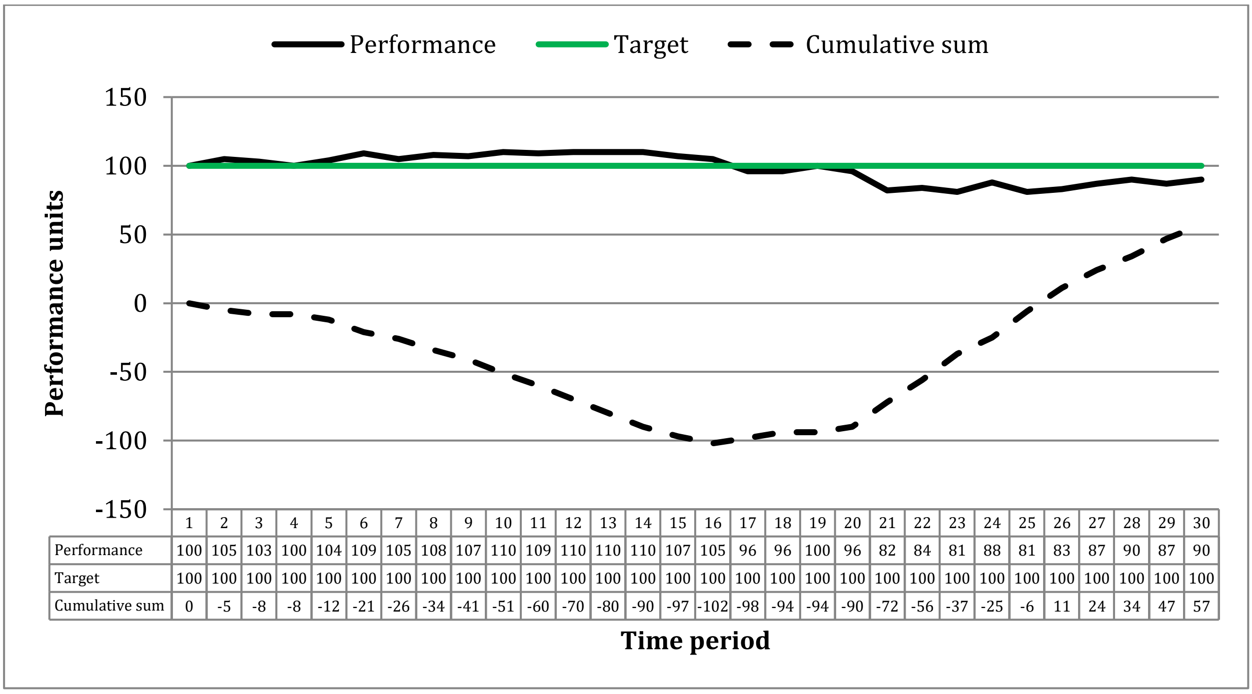


Figure 17: Energy wastage is identified more easily by understanding energy drivers

2.3.3 Review of energy performance measurement strategies in literature

A basic method that is often associated with monitoring and targeting is cumulative sum analysis [16], [42], [83]. This technique compares the running sum of performance with a target. When energy saving initiatives are implemented, a positive slope is expected on the graph, while a negative slope will reflect a decline in performance. This form of analysis can be useful for tracking a system’s performance over time.

Figure 18 shows an example of the cumulative sum technique. In this graph, the system underperforms from Time Period 6 to Time Period 15 (black line at top of graph) by being higher than the target (green line). This results in the cumulative sum line (dashed black line) having a negative slope. From Time Period 21 to Time Period 30, the performance improves and exceeds the target, leading to a positive sloping graph.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Performance	100	105	103	100	104	109	105	108	107	110	109	110	110	110	107	105	96	96	100	96	82	84	81	88	81	83	87	90	87	90
Target	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Cumulative sum	0	-5	-8	-8	-12	-21	-26	-34	-41	-51	-60	-70	-80	-90	-97	-102	-98	-94	-94	-90	-72	-56	-37	-25	-6	11	24	34	47	57

Figure 18: Example of the cumulative sum technique

However, part of the technique design is that some time periods may include under- or overperformance, which is expected to average out over time. The method is typically meant to be employed over several weeks to allow this averaging out. This means that this method appears to be ineffective at detecting underperformance at an operational level in the short term.

Another method proposed for monitoring energy performance is regression analysis [42]. Regression analysis is a simple method for modelling an energy-consuming system using energy as a dependent variable, and some independent variable as an energy driver. The expectation is that a relationship can be established. According to this relationship, energy use should increase whenever there is an increase in the independent energy driver. Typically this relationship is characterised as a simple first-degree linear equation [41], shown as Equation 3.

$$y = mx + c \tag{3}$$

Where:
y is the resulting energy consumption.
m is a factor relating changes in the energy driver to energy consumption.
x is the independent energy driver.
c is a constant baseload present in the system.

This methodology has also been used for assessing the performance of industrial DSM projects [85]. Typically, this method is applied on an aggregate basis, with the highest resolution of daily data points. However, it may still be feasible in smaller intervals. A further problem to this method is that it is chiefly useful for detecting changes in energy performance. Existing inefficiencies are likely to be incorporated into the model, meaning that they will not necessarily be detected and removed. Another common problem is that in many industrial cases, it is very difficult to find a measurable independent energy driver that is a good predictor of energy consumption. An example of this will be provided in Section 4.4.

Even so, the regression method is widely used and can potentially form a step in the process of implementing operational energy management. However, to achieve a sufficiently accurate model, a more complex method is typically necessary.

Vijayaraghavan and Dornfeld [66] discuss the shortfalls of accounting and theoretical approaches to energy analysis. They state that an accounting-based approach to analysis is typically not granular enough. This is because an accounting type analysis, as is often done when budgeting, is on a yearly and monthly basis, with no further breakdown as it is currently done in many South African industries.

Further, Vijayaraghavan and Dornfeld state that a theoretical approach does not provide sufficient accuracy in complex systems [66]. For operational energy management, this approach is especially unsuited as theoretical approaches are passive and do not have active components. Although opportunities for projects and initiatives can be identified this way, it is not supportive in providing real-time feedback. As such, a better method is needed, which the authors provide.

One of the contributions provided by these authors is a temporal analysis framework (Figure 12) [66]. This framework is targeted at event and complex event stream processing. This system is purportedly very flexible, but requires that site personnel still identify and develop rules for the analysis. However, no detail is provided on how this should be done for the method to be replicated.

In a significant work developing models for organisations to evaluate their own level of energy management maturity, Introna *et al*. [37] identify an important consideration in the analysis phase. The authors indicate that organisations can elect to analyse only energy consumption data, or other indicators as well. The authors indicate that considering other factors that contribute to energy consumption allows the model to understand the factors that underlie energy use, allowing for reliable forecasts to be made regarding energy consumption.

Hooke *et al.* [16] provide a few guidelines on energy data analysis. They recommend that both performance indicators and targets be used. These targets should be developed from a model of the process, the performance of other similar processes (benchmark), or statistical analysis. They also advocate for the understanding of underlying energy use to effectively manage it. In developing energy targets, this work emphasises that the energy targets need to be realistic, yet not easy to achieve. Further detail on how to implement such an approach is not included.

A significant contribution is made by Giacone and Mancò [49] who provide a framework for measuring energy efficiency in industrial processes. In this work, the authors recommend establishing a system boundary and statistically analysing energy consumption within the boundary along with energy drivers. This analysis results in a model of the system, which can be verified with actual measurements.

Using this model, the authors propose a matrix model for an entire factory. This, along with the specific energy consumption of each system, can then be used to determine the energy requirements of the entire factory. This approach serves to identify the need for understanding the action of systems as energy drivers for other systems.

One potential flaw in the framework is the use of a statistical black-box analysis to model process energy efficiency. This methodology, although effective and widely used, captures existing inefficiencies within the model. This results in a reference point that includes inefficiencies in the target. Further, as the authors note, this approach requires a large amount of data and information. A clear strategy for implementing the approach is also not provided.

The capturing of existing inefficiencies is illustrated in Figure 19. The process illustrated was already underperforming when the characterisation was implemented, which led to inefficiencies already in place to be captured as shown by Point 1. From this point on, performance is measured against this reference point, as shown by Point 2. However, the actual best performance of the process is not considered as shown by Point 3.

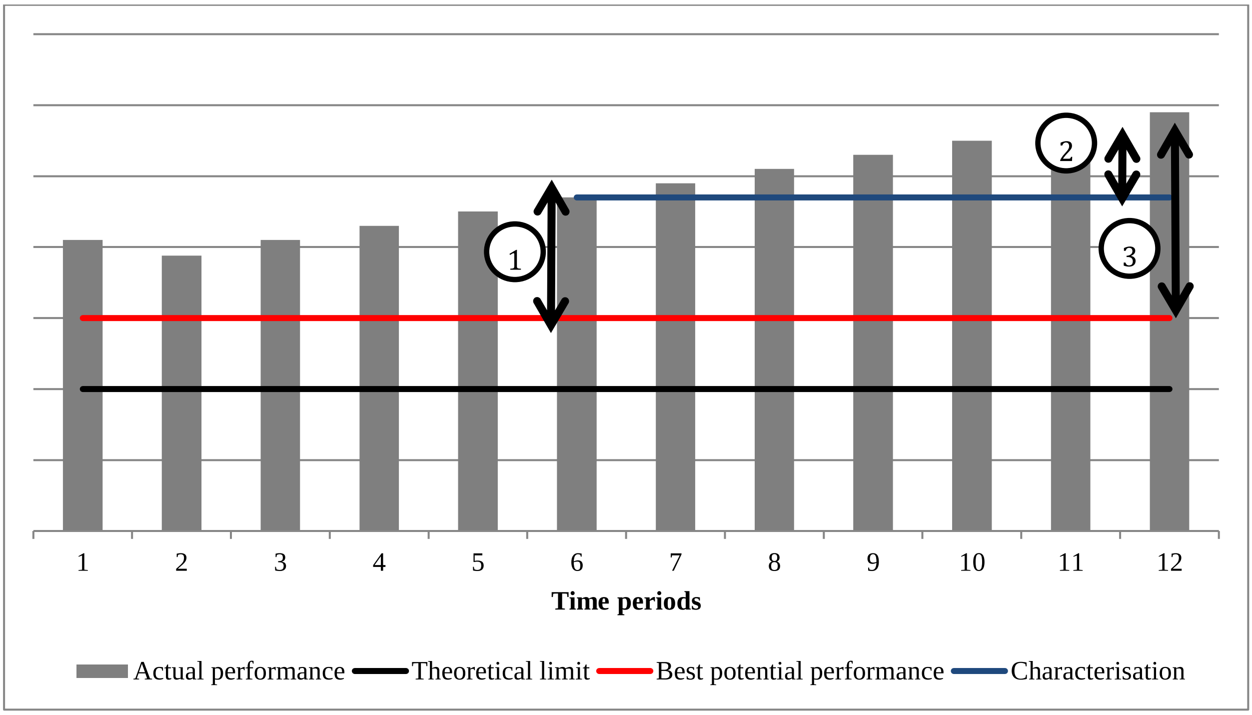


Figure 19: Capturing of existing inefficiencies using a black-box characterisation

KPIs, or energy performance indicators, are widely used and are a requirement of ISO 50001 [39]. Energy KPIs are typically indicators describing the relationship between an activity and required energy [36]. One potential problem with using KPIs is that they are typically made to be used at an aggregate level [36]. This means that they are intended to track performance over a time period. A well-designed KPI system may also be able to identify a trend. However, KPIs typically cannot provide corrective action, unless they are broken down to great detail.

May *et al.* [65] provide a framework for developing energy KPIs. Significant attention is given to energy used that is not part of useful production. Energy lost during stops, maintenance and machine changes is quantified and compared with energy used in production, with the ratio of the two factors being used as the energy KPIs. This is illustrated in Figure 20.

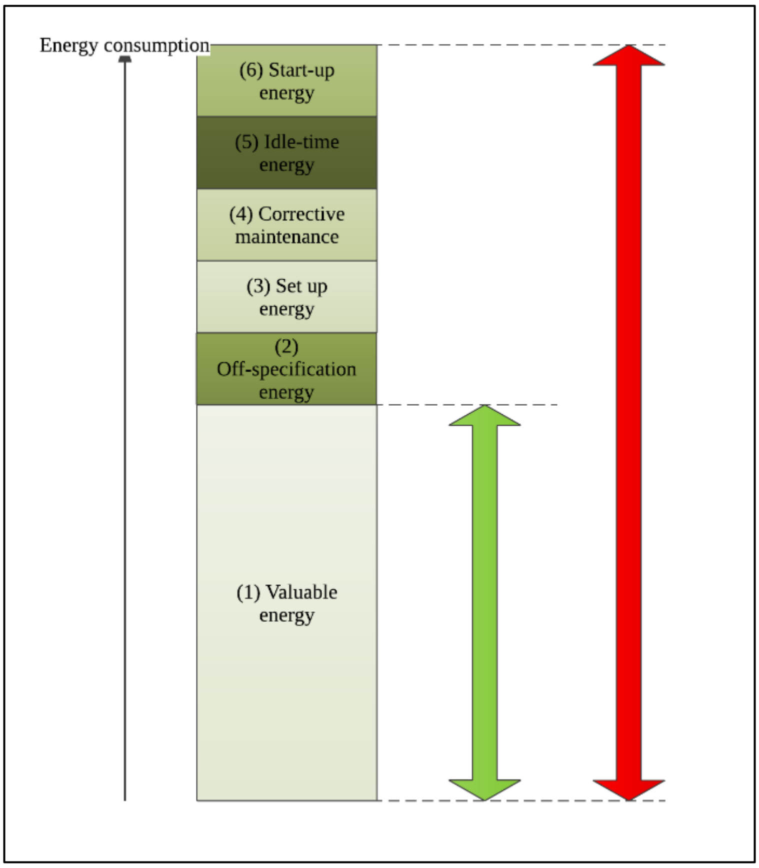


Figure 20: Example of KPIs developed by May *et al.* [65]

In this methodology, energy consumed, which resulted in a product being produced, is quantified, indicated by (1). Energy consumed, which resulted in a product that was not of the correct specification and needed to be reworked or scrapped, is quantified as (2). Energy consumed to set up machinery (3), for corrective maintenance (4), idling (5), and during start-ups (6) is also quantified. The ratio of the total energy (indicated by the long red arrow) is compared with the valuable energy consumption (short green arrow). By acting to move this ratio closer to 1, energy performance is improved.

This methodology is primarily useful in identifying waste that occurs due to consuming energy without producing a useful product. By implementing this methodology, any time unnecessarily spent idling machinery or performing other wasteful activities is identified, and reducing this consumption is encouraged. However, this methodology is not able to identify energy that is wasted as part of the valuable energy where energy performance is low. Factors that influence energy efficiency other than wasted time are not considered. The focus of this work is also on electrical energy, although some of the principles could be applied to other energy carriers.

A summary of the contributions and limitations from literature is provided in Table 7. From this summary, the requirements and considerations for the methodology that will be developed in Chapter 3 can be determined.

Table 7: Summary of literature regarding energy data analysis

Authors	Contributions	Limitations
ISO [72]	Requirement: Actual energy must be compared with expected consumption.	Provides only a requirement. No input regarding how expected energy consumption should be determined.
Department of Energy [42]	Regression and cumulative sum analysis.	Techniques not suited for operational energy management. Many industries are difficult to characterise using regression models.
Hooke *et al.* [16]	Recommends implementing energy targets based on statistical analysis or model.	Does not provide strategy for implementing such an approach.
Vijayaraghavan and Dornfeld [66]	Recommends not using a theoretical or accounting-based approach to analysis.	Does not provide a strategy for analysis that can be replicated in industry.
Giacone and Mancò [49]	Identifies the need for understanding how systems act as energy drivers for each other. Energy performance models must be verified with actual data and measurements.	Does not provide strategy for implementing the recommended approach. Reliant on black-box analysis.
Bunse *et al.* [36]	Identifies that KPIs are mainly used at aggregate level.	–
May *et al.* [65]	Method for developing energy KPIs based on operating states.	Does not consider factors that contribute to wasted energy other than wasted time.

2.4 Correct use of energy feedback

2.4.1 Overview

Feedback is the final step in the operational energy management process. By providing feedback, personnel are alerted to situations that require corrective action. Although feedback is conceptually simple, there are many problems with the way feedback is implemented in industry. Feedback is only effective if it promotes corrective action.

Feedback is a simple concept where the outputs of a process are used to adjust the process and improve future performance. In energy management, it is simply information that can be used to improve performance. Because it can be regarded as forming the basis of improvement, it is a critical step in any form of energy management. The basic concept of feedback is shown in Figure 21.

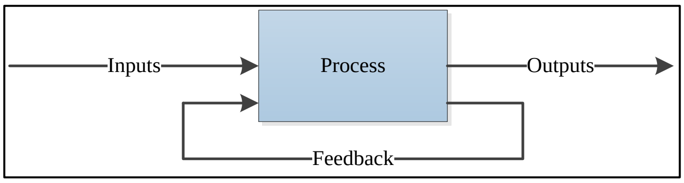


Figure 21: Basic structure of a feedback loop

Figure 22 shows a simple diagram of how feedback is applied in energy management. The inputs of the process are measured and used to determine the target performance of the process. This target performance is compared with the actual performance as measured at the outputs. Deviations from target performance are identified and reported as part of the feedback information. This information can then be used to adjust the process to remove deviations.

Although theoretically simple, in many cases feedback is not effective at achieving this improvement. There are many contributing factors. Effectively determining target performance was dealt with in Section 2.3. In this section, however, the focus will be on ensuring that feedback is provided in a way to make it effective. Feedback on energy use is crucial to operational energy management. Feedback helps by:

- Delivering information on potential for improvement,
- Assisting in making choices to achieve these improvements, and

- Assisting top management in determining whether policies are working.

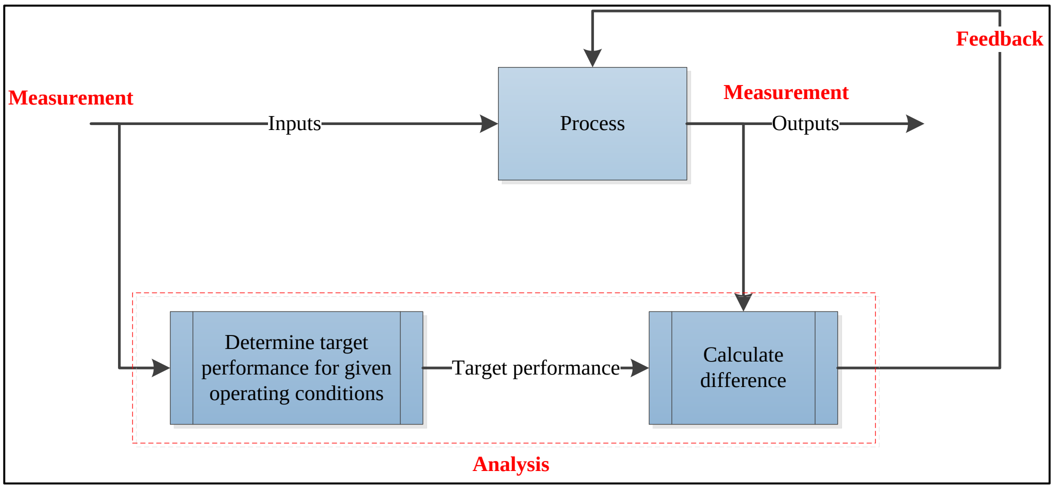


Figure 22: Basic diagram of feedback used in operational energy management

2.4.2 Existing energy reporting and feedback strategies

Feedback strategies employed in industry

There are significant problems with feedback strategies currently employed in South African industry. The first significant problem is that energy feedback reports are seen only as a tool to track performance. The capability of energy feedback to aid intervention and drive improved energy performance is often overlooked.

A significant portion of energy feedback's scope is not utilised. Figure 23 shows actions that form part of energy feedback, with areas not typically implemented shown in dashed boxes. The next step after evaluating the general performance of a system is to identify specific areas that underperformed. Following this, specific causes for underperformance can be identified. Finally, corrective actions can be provided.

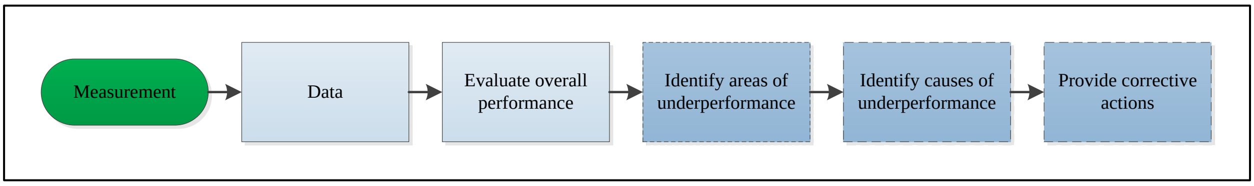


Figure 23: Full scope of energy feedback

A lack of automation of feedback systems has resulted in a single format of feedback, which is intended for a wide audience. These single-format types of feedback typically contain mostly raw or summarised data with a very low level of analysis. Because the intended audience for this feedback is so large, it is often too general to be able to identify specific areas for improvement.

Table 8 shows the results from a survey conducted of South African industrial companies. In most companies, some form of daily feedback is provided. However, the state of the feedback employed is poor. The focus of these feedback reports is to report energy performance upward in the company hierarchy.

Table 8: Survey of feedback employed in South African industrial companies

Industry	Company	Feedback employed
Gold mining and refining	GM Group 1	Weekly reports on facility and system energy consumption. Feedback discussed with facility energy representatives on a weekly basis.
	GM Group 2	Daily feedback on energy usage performance for entire facility – no information regarding individual systems or problem areas.
	GM Group 3	Daily feedback on energy usage and cost performance. Over-budget systems identified. No information on specific issues to be addressed.
Steelmaking	SM Group 1	Monthly feedback, 10 days following month end.
	SM Group 2	Daily feedback on energy usage and cost performance. Feedback in the form of summarised data. Corrective actions not identified.
Cement-making	CM Group 1	Informal feedback varying at different facilities.
	CM Group 2	Daily feedback of some facilities. Feedback in the form of summarised data with little or no analysis.

A core problem to implementing operational energy management in industry is the lack of feedback at the operational level. When an exception occurs, it is only discovered when scheduled weekly or monthly reports are generated. This is shown in Figure 24. Without the operational feedback loop, feedback must first pass through higher levels. This process usually occurs over several weeks, meaning that actions to arrest energy waste take a long time to be implemented.

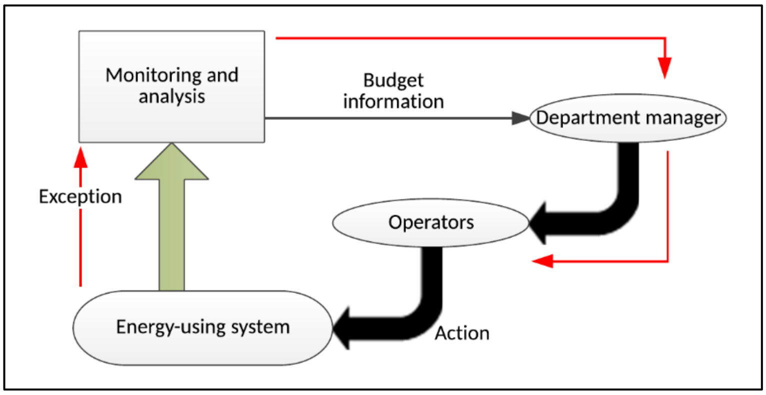


Figure 24: Exception handling practised in industry

Automation is also a significant problem in industry. In many cases, energy feedback is dependent on the energy management team. All data is routed through this team, where it must be analysed alongside historical or budget data to determine performance. The results are then presented to management. In some cases, the results may be discussed with plant personnel. However, due to the large scope and extended delay, this is an ineffective process. Figure 25 shows this process.

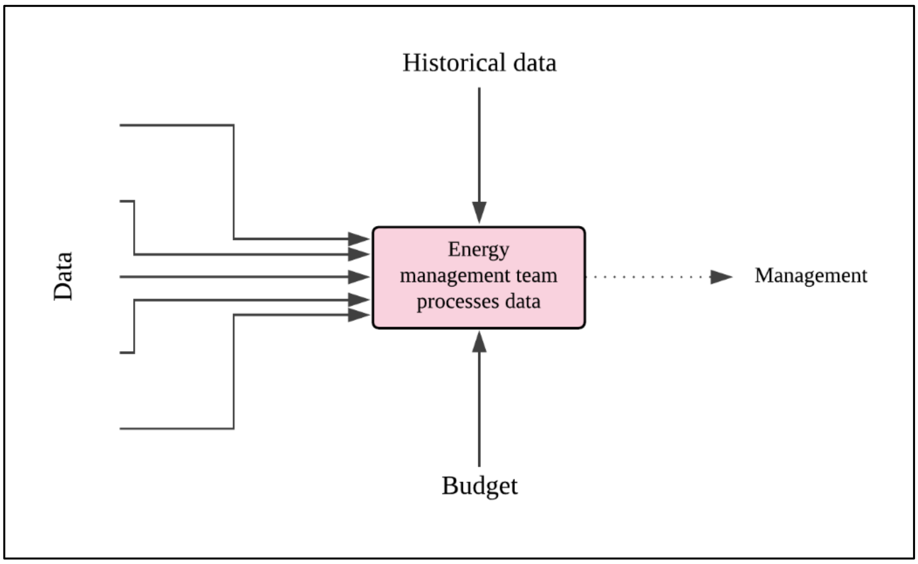


Figure 25: Energy feedback routed through energy management team

Another major problem found in several industries is the lack of a verified source of data. A typical occurrence is for a report or spreadsheet type document to be developed ad hoc and based on data that was easily available. Other reports may then be based on the new report as source document.

As a result, there are many instances of reporting on what should be the same logical value, but is actually a completely different data source.

A typical example of this is a power data tag. One such a tag may reflect the summated value of several different meters in a system, while another sources data from a meter located in the feeding transformer. In such a case, there are usually small but material differences between the two readings, but they are often used interchangeably.

One of the major reasons why this is a problem is because it results in unreliable evaluation of performance. If one data set is used for a baseline year, and another is used the following year to evaluate it against, a change in performance might be calculated. This change may however be purely because of a change in the scope of the two data sets.

Feedback strategies in literature

Three types of feedback are identified by the ETSU in the United Kingdom [89]:

- Scheduled – normally planned feedback in planned intervals, such as daily, weekly or monthly.
- Exception – feedback triggered by a specific set of circumstances.
- Ad hoc – feedback generated upon request.

Scheduled and exception reporting are considered for operational energy management purposes. Scheduled reporting is often employed to monitor performance versus a budget or target figure. This manner of reporting will often compare a period’s performance versus the target, giving an indication as to whether the average performance is meeting the target. This type of reporting is more appropriate for strategic and planning functions.

Exception reporting is often employed in situations where process or system performance targets can be set in terms of energy demand. This means that the performance can be measured in real time, and instances of underperformance can be identified immediately. In such an event, the relevant personnel must immediately be notified to intervene and avoid energy wastage.

Both types of feedback can be employed for the other's purpose. For example, exception feedback can be generated once a system has exceeded the daily energy consumption budget. Scheduled feedback can also be employed to report on exceptions.

Early work on the subject of complete systems to provide feedback was done by Askounis and Psarras [64]. In this study, a monitoring and targeting system was implemented on a Bulgarian brewery. The developed system relied on data that was only collected monthly. Given available technology, more effective daily feedback would have been difficult to achieve and require far more manpower. By implementing a complete system to provide feedback on a monthly and annual basis, performance could be reported reliably.

Swords, Coyle and Norton [90] developed a system capable of providing feedback on webpages based on analysed meter data. This system required action from users to retrieve feedback, and analysis ability was available through further interaction. This work was implemented in an industrial and commercial setting. The authors emphasised the need for the system to fully integrate into existing systems, thereby ensuring that it is maintained and forms part of management practices. However, this system was aimed primarily at providing summary data without capability of identifying exceptions and their causes.

One difficulty associated with effective operational energy management is a lack of authority over personnel responsible for energy use [41]. For this reason, it is important that feedback forms part of operational practice and flows directly to operators. ETSU also showed through a specific case that feedback should be reported in a way the recipient finds relevant [89].

Other principles identified by ETSU specific to large companies are [41]:

- Relevant information must reach the correct personnel capable of acting on the information provided.
- The information must be easy to understand and act upon.
- The information must not be hidden amongst unnecessary additional information.

The Industrial Energy Management course provided by South Africa's Department of Energy [42] provides a framework for reporting. This framework incorporates information from international best practices such as the Good Practice Guide 231 [89]. Several important considerations for developing feedback are identified. These include:

- Information required by recipients.
- Speed of feedback.
- Frequency of feedback.

Table 9 shows a summary of the different types of report required at different levels of decision-making within an industrial organisation. Typically, the annual report contains a broad summary of information, which is useful in indicating an upward or downward trend. Monthly reports are used by accounting in conjunction with utility bills. Monthly reports also assist supervisors in determining the overall performance of a system.

Table 9: Summary table of information required by different recipients (adapted from [89])

	Annual report	Monthly report	Weekly report	Exception report	Key indicators
Executive	Y				Y
Accounting	Y	Y			Y
Departmental heads	Y		Y	Y	Y
Purchasing	Y				Y
Supervisors		Y	Y	Y	Y
Workforce					Y

Weekly reporting is used in planning, where small changes may be able to improve performance. Exception reporting is important as it can follow closely to exception events. Receiving and acting on these reports quickly enough may help arrest energy waste. KPIs are useful at all levels by assisting personnel in determining whether required performance levels are being met. However, KPIs typically do not contain sufficient information to assist personnel in identifying reasons for not meeting performance targets.

The Department of Energy also provides a model for reporting, as shown in Figure 26. Measurements are incorporated into the monitoring and analysis system to provide information to the various relevant parties. Each party uses the information to take action on the role player below him, resulting in action being taken on the energy-consuming system.

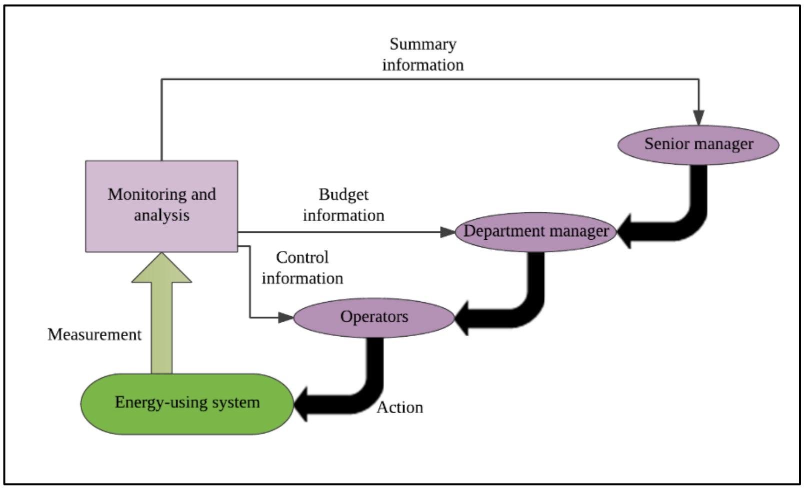


Figure 26: Model for energy reporting (adapted from [42])

A single report applied to all levels is not suitable [43]. This is because there are different decision-making responsibilities at different levels. This is also reflected by the different informational needs at different levels, as shown in Table 10. Control is far more reactionary at the operational level. At the managerial level, decisions are made to broadly improve results.

Table 10: Information needs for different planning levels (adapted from [42])

Level of decision-making	Information	Operational control	Managerial control	Strategic planning
Information needs	Source	Internal	Internal	External
	Precision	High	Medium	Low
	Timing	Exceptional	Periodic	Irregular
	Notice	Sudden	Anticipated	None
	Nature	Warning	Results	Predictive

Maneschijn *et al.* [44] provide recommendations on energy reporting based on three categories, namely, content, temporal considerations and implementation. The authors postulate that energy reporting is more effective the more processed the contents are. Providing raw data is considered the least effective, while providing performance information such as KPIs is the most effective. The authors do not, however, mention that identifying the causes of non-conformance or potential corrective action can improve the reaction rate and time on such reports.

As a general guideline, Maneschijn *et al.* [44] state that reporting should be closer to the occurrence of energy use at the operational level and take place more frequently. The further away the recipient is from the operational level, the less frequently reporting is necessary and it can occur further from use. This is since managerial and executive personnel often do not have direct control over machines, and are instead more focused on changing strategy to improve results, rather than direct action.

Finally, regarding implementation, the authors point out that feedback should be automated as much as possible. This is to ensure that the energy management team have sufficient time to perform their core duties. The major limitation of this work is that it does not provide a comprehensive method for implementing reporting. It does not show how stakeholders receiving reports can be identified, or how to develop a report for each stakeholder. This work only provides vague guidelines.

Vijayaraghavan and Dornfeld [66] identify the importance of considering timescale when developing feedback in machining plants. They state that decisions are made at different levels in manufacturing – meaning that each level may have different requirements. Levels closer to the physical production layer (process control) make decisions on a second-to-minute scale, while management make decisions affecting hours and days. This theory can be adjusted and applied to industrial manufacturing to serve as criteria for feedback development.

In early work on the subject of energy reporting, Glemmestad *et al.* [67] developed a reporting system for Norsk Hydro. The authors present four requirements for a reporting system in a large company, namely, accessibility, user-friendliness, confidentiality and maintenance. In terms of accessibility and user-friendliness, the authors state that everyone within the organisation must have access to the reporting system, and that anyone with basic computer experience must be able to use it. This reasoning is no longer suitable in modern industries. The primary problem is that it places the onus on personnel to retrieve energy performance reports from the system. As previously stated, most involved personnel do not have the time to participate actively, and reporting should therefore be automatically directed towards them.

Further considerations in this paper are technical aspects such as confidentiality of information and ease of maintenance. The type and quality of information being reported is not analysed critically. Reporting is available on demand and contains significant amounts of data and little processed information.

In a series of case studies, Motegi *et al.* [68] identify the need to provide operators with information in a condensed graphical format. This would help operators interpret the large amounts of data more easily. This work assists in identifying a key consideration in operational energy management – where possible, feedback should be simple enough to not require further interpretation. The closer the provided feedback is to providing a decision for plant personnel, the more likely it is to be effective.

In the specific case of a car manufacturing company, Gordić *et al.* [47] provide a case study of implementing an energy management system including feedback. In this study, the authors show that stakeholders are identified as part of the management process, but not how they are identified. Further they assert that the energy management team should review feedback on energy consumption and production daily. More in-depth indicators should be reviewed on a weekly basis, and appropriate remedial action taken when necessary. This approach is not suitable in complex industry with small energy management teams and many points of consumption to monitor. The energy management team also typically do not have the authority to act directly in large industrial facilities.

Retsina [91] patented a method and system capable of providing feedback. This work relies on three levels of targets that are used to monitor an entire facility's level of energy performance. The second level includes departmental KPIs. Finally, key energy parameters are identified for specific equipment that have a significant effect on energy performance. These parameters are determined from historical data.

This work does not provide for dynamic notification of underperformance, but rather relies on operators accessing the published reports to determine where faults are occurring. Provided targeting and monitoring reports also do not seem to indicate an ability to identify corrective actions. The method developed also relies on statistically significant deviations in performance over time, which means that small deviations may escape attention for long periods.

Goosen, Pelzer and Bolt [92] developed a system for monitoring the performance of Eskom-funded DSM projects. These are cost savings projects in industry funded by Eskom. The purpose of this system was to maintain the performance of projects by ensuring that regular feedback is given. This automated system was intended to provide daily reports that could identify non-performance and missed cost savings. The report contents are highly summarised, including savings target performance, electricity cost and two summarising graphs. The use of 24-hour profiles can assist in determining the specific time when deviations occurred.

However, the system is intended to report on a daily and monthly basis. Many DSM projects are aimed at shifting electrical load out of expensive evening peak periods. If there is a problem, this specific form of feedback will only provide an alert more than 12 hours later when the report is sent the next day. Although this should prevent an incident, this delay in feedback does result in a loss of savings. Further, due to being linked to a specific ESCo's projects, unnecessary steps are also added to the feedback loop in the form of ESCo personnel who must evaluate feedback first.

Further work by Goosen, Prinsloo and Pelzer [70] identify some additional considerations. The problem with reports containing too much information is pointed out. Further, Goosen *et al.* point out the most important consideration in feedback: *"Gathered data is only worth as much as the ability to convey the extracted information"*. However, the work again only provides information on whether a system is over- or underperforming, with no indication as to why or what corrective action is possible.

Bogdanski *et al.* [93] provide a method for energy feedback based on feedback theory. In this work, significant emphasis is placed on addressee-oriented feedback. This means that different feedback should be provided to different recipients based on their position as stakeholder. The work distinguishes between feedback for indirect and direct utilisers. An indirect utiliser in this context is identified as someone who does not have direct control of energy-using systems, such as management, while a direct utiliser affects energy use directly, such as an operator.

This work focuses heavily on KPIs. This leads to one particular shortfall being that recommended actions are not considered part of feedback. Although the presented method is effective for identifying situations where energy performance is not sufficient, this form of feedback still requires operators to identify problems and fix them on their own. As already discussed, this is not always suitable in the South African industrial environment where operators have other more pressing considerations. Further, this approach is specifically developed for electricity, which may not be suitable for other energy carriers.

From the literature reviewed, a summary of the considerations and requirements for feedback can be developed and is shown in Table 11. These results can be used to inform the development of an energy feedback system, as will be shown in the next chapter.

Table 11: Summary of literature regarding energy performance feedback

Authors	Contributions	Limitations
Department of Energy [42]	Considerations: Timing and frequency of feedback. Guideline reporting timelines.	Does not provide a comprehensive methodology for implementing feedback.
Askounis and Psarras [64]	Case study example of feedback in brewery.	Limited by available technology. Did not provide methodology or systematic process for implementing feedback.
Swords *et al.* [90]	Recommends integrating feedback into other parts of operations.	Aimed only at summary reporting, not operational management.
ETSU [41], [89]	Recommends that feedback is relevant to recipient, easy to understand and does not contain unnecessary information.	Does not provide a comprehensive methodology for implementing feedback.
Maneschijn *et al.* [44]	Considerations: Temporal scale of feedback, level of processing of contents, automation of feedback.	Does not provide a method to identify stakeholders or comprehensively implement feedback. Did not consider corrective action as part of feedback.
Vijayaraghavan and Dornfeld [66]	Considerations: Catering contents based on recipient level within organisation.	Does not provide a comprehensive methodology for implementing feedback.
Gordić *et al.* [47]	Consideration: Identify and report to stakeholders.	Example limited to specific case study.
Retsina [91]	Full method for determining energy performance and providing feedback.	Feedback is passive and relies on personnel actively seeking it. Statistical evaluations mean longer delays before poor performance is identified.
Goosen *et al.* [92]	System for reporting on performance of DSM projects.	Aimed at DSM projects.
Goosen *et al.* [70]	Considerations: Clear and easy to understand reporting, limiting information overload. Visual method for providing feedback.	Summary reporting with a single standard for all users. Feedback is passive and does not take energy drivers into account.
Bogdanski *et al.* [93]	Addressee-oriented feedback, use of KPIs.	Does not provide for identifying causes or corrective action. Does not provide a comprehensive method to implement feedback.

2.5 Requirements

Based on a critical analysis of methodologies currently used in industry and literature, the requirements for an effective operational energy management system are now known. This is summarised in Table 12, which also shows relevant literature that has identified or contributed to each of the identified criteria, considerations or requirements. No single literary work has incorporated all available work into a single effective operational energy management system.

Table 12: Existing work and requirements for operational energy management

Considerations, criteria and requirements		Vijayaraghavan and Dornfeld [66]	O'Driscoll and O'Donnell [59]	O'Driscoll *et al.* [60]	Hooke *et al.* [16]	Department of Energy [42]	Vikhorev *et al.* [58]	Du Plessis [82]	Introna *et al.* [37]	ISO 50001 [39]	Giacone and Mancò	May *et al.* [65]	Good Practice Guides [41], [89]	Askounis and Psarras [64]	Swords *et al.* [90]	Maneschijn *et al.* [44]	Glemmestad *et al.* [67]	Motegi *et al.* [68]	Gordić *et al.* [47]	Retsina [91]	Goosen *et al.* [92]	Goosen *et al.* [70]	Bogdanski *et al.* [93]
Measurement	Systematic process to understand energy distribution				○		○																
	Systematic method						○																
	Criteria: metering automation	○																					
	Criteria: metering resolution		○																				
	Criteria: metering sampling rate		○				○																
	Criteria: metering accuracy		○			○																	
	Criteria: temporal scale	●																					
	Criteria: cost of metering					○																	
	Meter calibration				○																		
	Energy drivers					○																	
	Data standard	●					○																
	Data availability strategy	○			○																		
	Data integrity strategy							●															
	Methodology			○	○																		

Considerations, criteria and requirements		Vijayaraghavan and Dornfeld [66]	O'Driscoll and O'Donnell [59]	O'Driscoll *et al.* [60]	Hooke *et al.* [16]	Department of Energy [42]	Vikhorev *et al.* [58]	Du Plessis [82]	Introna *et al.* [37]	ISO 50001 [39]	Giacone and Mancò	May *et al.* [65]	Good Practice Guides [41], [89]	Askounis and Psarras [64]	Swords *et al.* [90]	Maneschijn *et al.* [44]	Glemmestad *et al.* [67]	Motegi *et al.* [68]	Gordić *et al.* [47]	Retsina [91]	Goosen *et al.* [92]	Goosen *et al.* [70]	Bogdanski *et al.* [93]
Analysis	Theoretical method	○																					
	Graphical method				○	○																	
	KPIs				○					○		○											
	Targets				○					○													
	Energy drivers								○														
	Process model				○																		
	Methodology	○									○	●											
Feedback	Single verified data source																						
	Contents					○							○			○							○
	Stakeholders																						○
	Temporal scale	●														●							○
	Frequency																						
	Analysis levels															○							
	Performance feedback					●	○							○	○				○	●	●	●	○
	Improvement areas	○																		○			
	Methodology					○	○						○					○		○			●

2.6 Conclusion

In this chapter, the three major components of operational energy management were discussed. Existing practices in industry relevant to operational energy management were reviewed. These practices, although useful for identifying the challenges facing industry regarding operational energy management, did not provide evidence that operational energy management is being practised effectively in industry. As was discussed in the previous chapter, it was found that energy management practices in South Africa are still in a relevant state of infancy.

Literature relevant to operational energy management was comprehensively reviewed. It was found that several studies relevant to the practice have been conducted. However, there were two pervasive limitations to existing literature. Firstly, there are very few studies or guides that provide an integrated view of operational energy management. The few studies that do integrate measurement, analysis and feedback, do so at a very high level. These guides do not provide sufficient detail or a method to implement operational energy management. Instead, only a few very specific items are explored, and very general ideas are provided.

The second category many existing studies fell into was focusing on a specific component of operational energy management. Most of these studies provide only a few very specific guidelines for a small component of operational energy management. None of the reviewed literature provides a comprehensive methodology for implementing operational energy management.

However, by reviewing the literature and identifying the state of operational energy management, these concepts could be integrated into the requirements for a methodology for operational energy management. This, combined with knowledge gained from industry, will form the requirements of the methodology to be developed in this study. This will be done in the next chapter.

Chapter 3 Developing a system-based approach for operational energy management

3.1 Preamble

In the previous chapter, the requirements for an operational energy management system were identified. In this chapter, these requirements will be used to develop a methodology for implementing operational energy management. The methodology will be described in three broad sections. First, a methodology for energy measurement and data management will be described. The next part will develop a unique methodology for analysing energy data. Finally, a new strategy for energy feedback will be presented. This is shown in Figure 27.

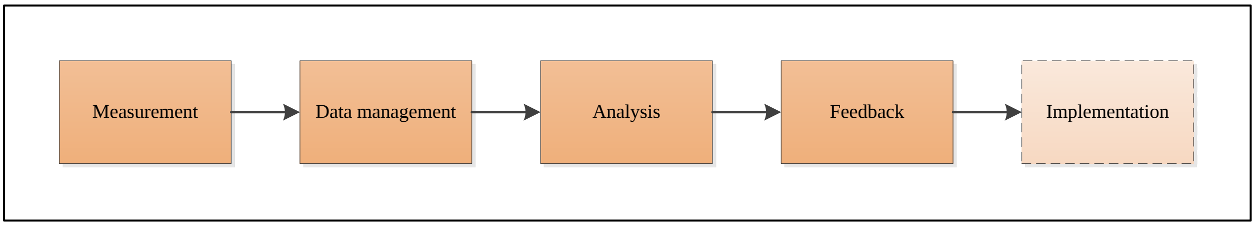


Figure 27: Operational energy management process overview

3.2 Overview of the system-based concept

This methodology will follow a system-based approach. In most industrial facilities, logical systems have already been identified. A list of typical systems found in several South African industries is shown in Table 13.

Table 13: Typical systems found in several industries

Gold & platinum mining	Cement manufacturing	Steel manufacturing
Winders	Raw material crushing	Coke ovens
Refrigeration	Raw meal grinding	Blast furnaces
Dewatering pumps	Calcination	Basic oxygen furnaces
Compressors	Cement grinding	Compressors (including or excluding blast air)
Ventilation	Mixing	Hot rolling mills
Processing plants	Transport compressors	Cold rolling mills
Smelting		Generation
		Steam

In this context, a system is a production or supporting unit that performs a certain specific function. A system requires certain inputs to perform this function, and may also be affected by other factors. Given the required inputs, the system can perform its task and provide an output. This output may support the production process as a whole, or may be part of the process itself.

Most industrial production facilities in South Africa have more than one system. These systems may be arranged in a series of production steps. Other systems are supporting systems, which take no part in processing materials but provide a service to systems that do. For example, compressed air plants on deep level mines supply compressed air underground used to operate processing machinery. This is illustrated in Figure 28.

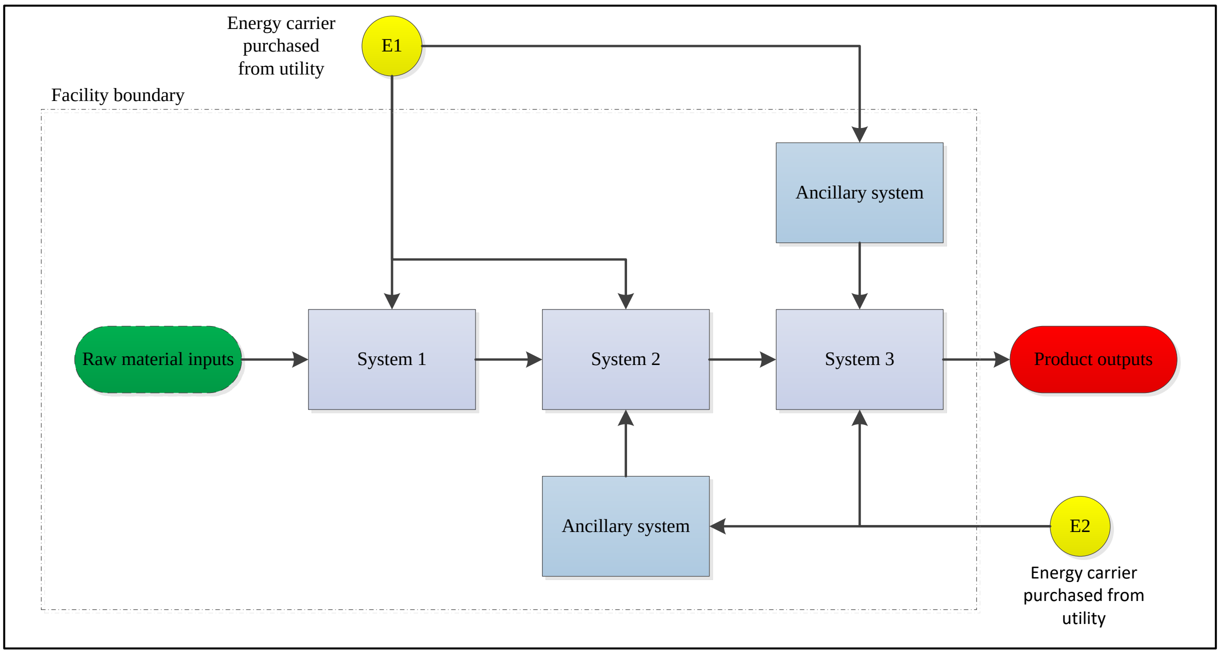


Figure 28: A production facility illustrated as an arrangement of systems

Typically, a production-related system will receive some material input. For example, a blast furnace receives iron ore and coke as materials. Energy is typically added to change the qualities of the materials, be they chemical or mechanical qualities. In the example, energy is added to the system with blast air and pulverised coal. Finally, the result is a processed output product. For example, molten iron and slag are produced by the blast furnace.

In supporting systems, the product is not something that will eventually be sold, but will rather provide a service to other systems. This is often in the form of an energy carrier. For example, a compressor system uses electricity and air to produce compressed air. Underground dewatering pumps are powered by electricity and remove water from underground.

3.3 New energy measurement methodology for operational energy management

3.3.1 Overview

This section will develop a methodology for energy measurement. Due to a lack of capital for energy management currently available in industry and the prohibitive cost of energy meters, this methodology will not take the approach of identifying locations for new meters. Instead, the focus will be on identifying which energy streams should be metered, and determining the quality of the measurements. This will allow energy managers to identify existing meters that may already be suitable for operational energy management.

The two aspects discussed above require some further clarification. When referring to metering scope or location, this document refers to the location on the physical energy stream where a meter is installed. With metering quality, this thesis refers to what qualities are being measured (such as volume or energy content), and how reliable the measurement is. It is necessary to see to both qualities for operational energy management.

The first part of this section will develop a systematic process for determining metering scope. By applying this, the user will be able to determine where measurements will be required. Second, a process will be developed for providing sufficient metering quality. The results from these two steps can be compared with available metering to determine which measurement points to use and whether additional metering is required. Finally, the methodology for managing energy data will be presented. These three methodologies practised together will satisfy the requirements for energy metering, as shown in Figure 29.

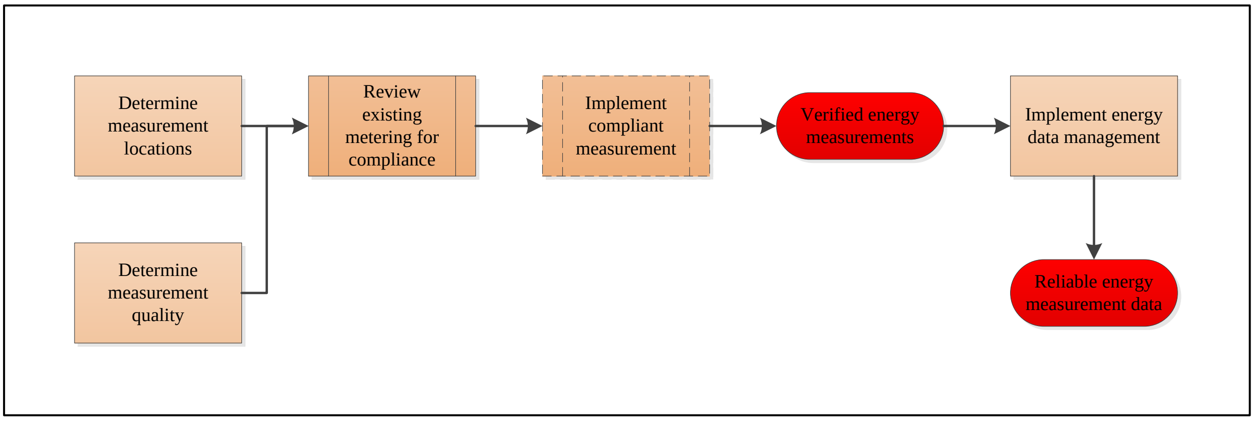


Figure 29: Methodology for energy metering

3.3.2 Part A: Establishing metering scope

For operational energy management, metering must be suitable for providing operators and other personnel with information regarding energy performance in such a way that problem areas can be identified quickly. Meters should be placed in such a location that the energy performance of systems can be measured.

Figure 30 shows a basic overview of the process that will be followed to identify where energy metering is required. The energy sources, energy-consuming systems and energy streams will be identified first. Due to the complexity of performing this task, a systematic method will be used to perform this step. Once this has been completed, the energy streams will be prioritised for measurement according to criteria suited to operational energy management.

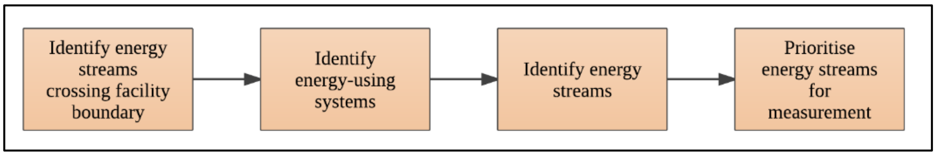


Figure 30: Basic systematic process for identifying metering locations

In this section, the following terminology will be used:

- System – a node in the energy network where energy is used to provide a useful service. This does not include distribution points.
- Origin – the point(s) where an energy carrier exits a system.

- Insertion – the point(s) where an energy carriers enters a system.
- Energy stream – energy being transferred from one system to another.
- Storage – a place where an energy carrier is stored for future use.

This is illustrated in Figure 31 for further explanation.

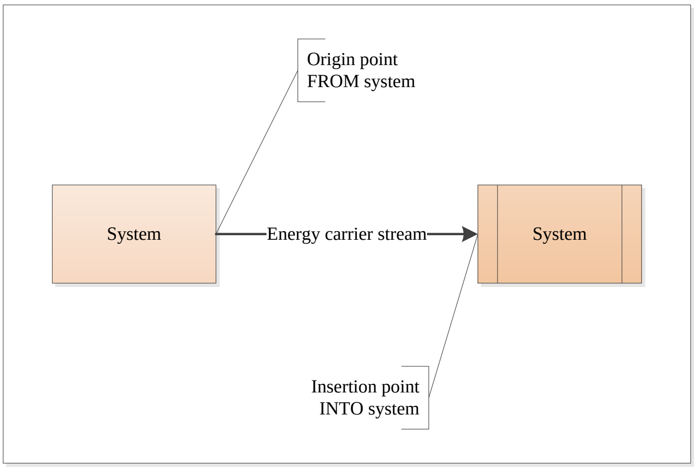


Figure 31: Illustration of methodology terms

Metering must be installed so that it is possible to measure the flow of energy into and out of systems. This may require that meters are installed where energy is distributed from, where it is transferred to, or where it is consumed within the system. The end result should be that the system's energy consumption can be determined with reasonable accuracy. This may mean calculating the system's energy consumption using the data from multiple meters.

Figure 32 shows an example of a facility layout with potential metering points identified. In this graph:

- Point 1 indicates the location of the utility or supplier's billing meter,
- Point 2 indicates the potential check meter used to verify the bill,
- Point 3 indicates the delivery into distribution points,
- Point 4 indicates the exit of the energy carrier from the distribution point,
- Point 5 indicates the entry of the energy carrier into the system, and
- Point 6 indicates the consumption by the end user.

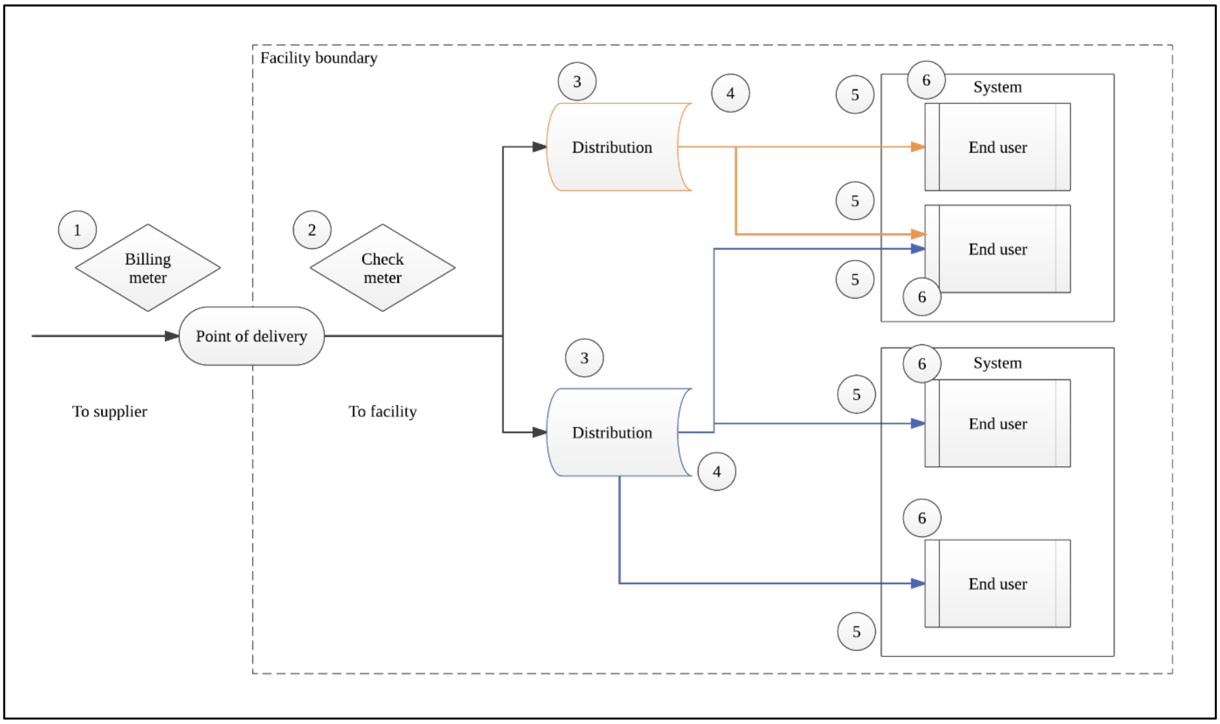


Figure 32: Example of metering points available for a typical facility

By law, there must be a meter installed at Point 1 as it is used for invoicing purposes. It is typically in the facility's own interest to have a check meter at Point 2 to verify the utility bill. This is often the only way to ensure that a fault in the supplier's meter does not persist for a long time leading to overcharging.

In many instances, facilities elect to install meters at the entry point of distribution systems. This is to assist in verifying meters. The sum of these meters should equal the checking meter or billing meter, after transportation losses (if any) are considered. The next level of meters should equal the distribution meters. In this way, the meters can be verified by comparison.

Meters at distribution points typically do not assist in achieving the goals of operational energy management; however, unless the distribution point is used to supply only a single system. Another potential problem with meters at these points is that energy carriers can potentially be stored within the distribution point for an indeterminate amount of time. For example, coal stockpiles may have several days' worth of stock. For burnable gas, this problem is reduced unless gas holders are present [94]; for electricity it is typically not a concern.

The next potential metering point is Point 4 where the energy carrier exits the distribution point. Depending on the layout of the distribution network, metering at this point may or may not be useful for operational energy management. If a common distribution line feeds multiple systems, this point is not useful.

Metering Point 5 is a point on the distribution line after it has split and that feeds only a single system. Where available, these metering points can be very useful for achieving operational energy management. However, depending on the architecture of a system, metering at this point may be prohibitively expensive due to the number of meters required.

A final option is metering Point 6, where the end users are measured. In many facilities, some meters are in already in place for process control. This can be an option; however, it is possible that some smaller end users may not be captured due to a lack of metering. Installing new meters here may also be prohibitively expensive due to the large number required.

Figure 33 shows a simplified diagram of energy use and distribution in industrial facilities. Energy carriers can be supplied either by a utility (electricity, natural gas) or as raw material (coal). The supplied energy is either used directly in the production process, or first converted to a more useful form. For example, electricity is often used to generate compressed air, and natural gas may be burnt in a boiler to produce steam.

Energy not stored in the product may be captured in another form, or may be lost as waste. For example, processes in a blast furnace will produce blast furnace gas [95]. However, the heat generated by a compressor is often not recuperated [96]. The energy may be captured in the final product produced by the plant, but this is often not the case. Rather, energy is typically applied to process raw materials into more usable forms. An important consideration is whether energy carriers are stockpiled or stored on-site. If so, the container must also be considered.

The methodology for determining locations of energy measurements will now be described. The methodology consists of an iterative process, moving from the point of delivery to end users. For each step, the energy carriers into and out of the system are determined. It should be noted that although the energy carrier may be viewed as a single line for methodology purposes, the carrier itself may have multiple corresponding transmission points. If this is the case, all the corresponding points must be grouped together and considered a single logical point. However, when calculating the costs for metering, the cost of instrumenting each strand should be taken.

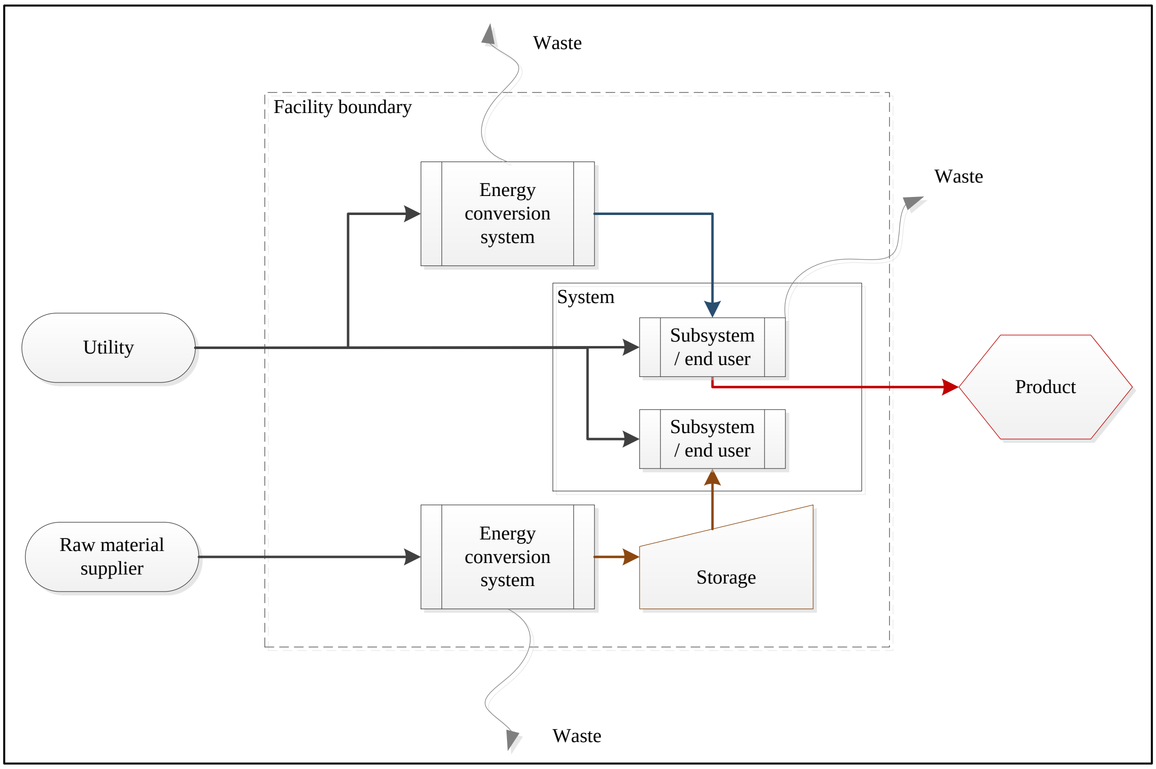


Figure 33: Common energy distribution and use in industry

It is important to note that the physical layout may differ from the logical view used in operational energy management. This means that certain physical features, such as an electricity substation, will not be indicated in the methodology. Metering of these systems will be at the discretion of the plant, as metering is often done for legal compliance or maintenance purposes.

Step 1: Facility boundary

All energy carriers crossing the facility boundary should be considered, which include utilities and raw materials. Energy that can no longer be effectively utilised, such as waste heat, will not be considered.[10] All energy carriers that cross the facility boundary must be listed. For each listed energy carrier, the number and quality of measurement devices necessary must be determined.

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[10] Typically, waste heat recovery, cogeneration and other similar interventions are large capital-intensive projects. The implementation of these types of project does not fall under operational energy management, and will therefore not be discussed in this thesis.

The number will be the least possible number that can be used to capture the full quantity. Raw material energy carriers should also be included. This is demonstrated in Figure 34.

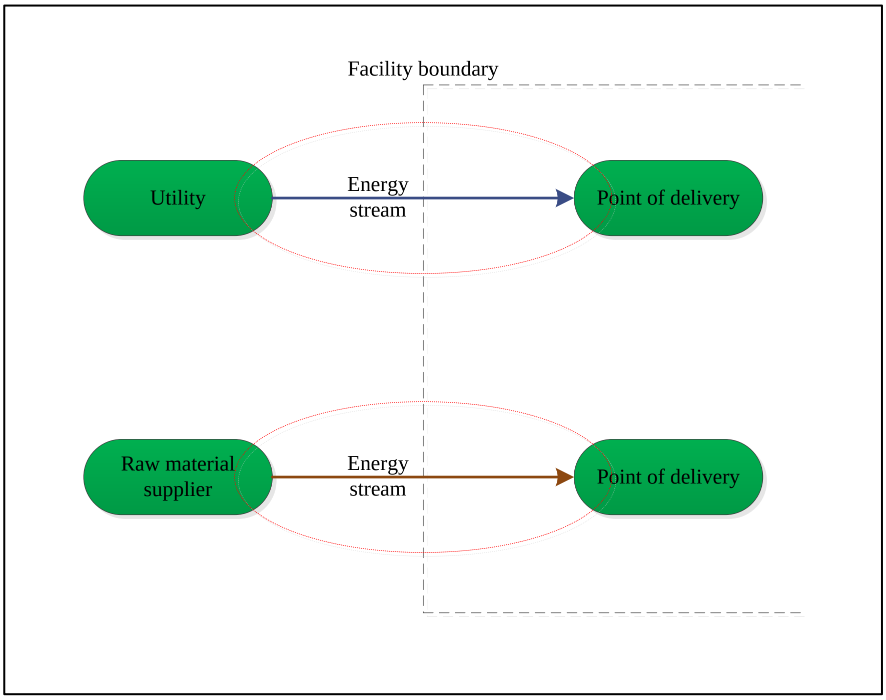

Figure 34: Step 1 – identify energy carriers transferred across facility boundary

The process should be recorded both in graphic and tabular format. In the table, the minimum number of meters required to perform the measurement is included. The total annual energy transferred through the carrier in both watt-hour/joule and cost value should be indicated if it is available. This can usually be retrieved from energy accounts. Otherwise, an estimated value can be substituted. An example of this is shown in Table 14.

Table 14: Summary of results of Step 1

Energy carrier	Minimum number of meters required	Total annual energy	Total annual cost of energy
E.g. Electricity	4	3 600 TJ	R700 million
E.g. Coal	1	4 000 TJ	R111 million

Step 2: System entry points from supplier

From the facility boundary, the next step is following each of the energy carriers to the next system. There may be distribution points (such as a substation) before the energy carrier meets a system, but these need only be considered if all other meters are already in place. Again, for each energy carrier, the number of metering devices that will be required to measure the line of transfer must be determined. This is demonstrated graphically in Figure 35. It should be noted that there may be other energy carriers entering these systems from within the facility, as indicated as green "point of delivery" blocks in the figure. These should be noted but not included at this point.

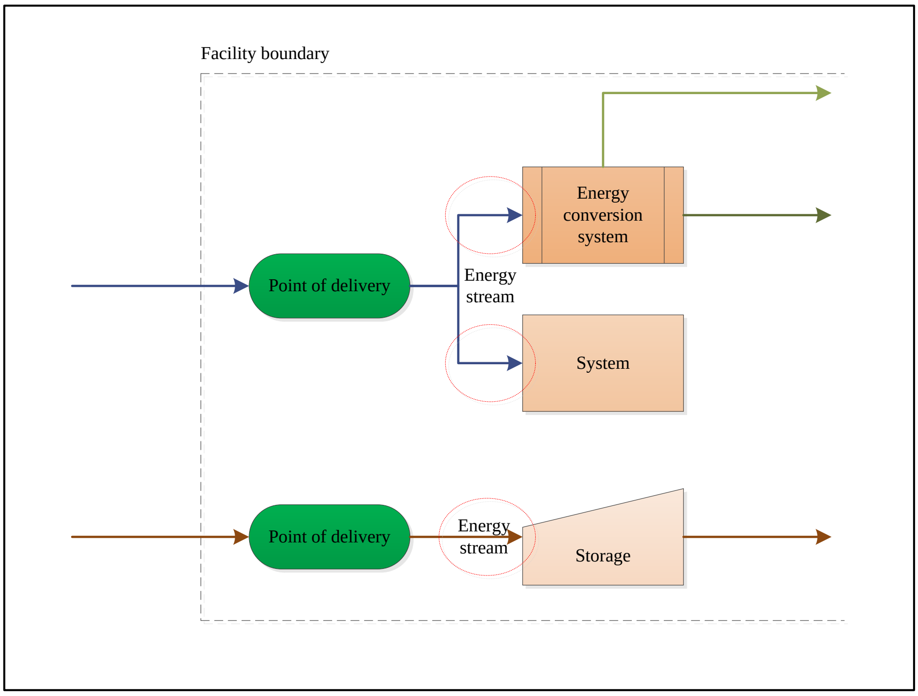

Figure 35: Step 2 – identify the entry point of each energy carrier into plant systems and storage areas

The energy carriers should again be tabulated, as shown in Table 15, and the energy input and cost of energy should be included if available. However, as this is likely not the case, attributed values may be used based on the rated energy use and running time of the systems in question.

Table 15: Summary of results of Step 2

Energy carrier	Minimum number of meters required	Total annual energy	Total annual cost of energy	Point of origin
E.g. Electricity	2	800 TJ	R156 million	Utility
E.g. Coal	1	4 000 TJ	R111 million	Supplier

Step 3: System exit points

The next step is to systematically note all the exit points of energy carriers being considered. This is illustrated in Figure 36. The results are tabulated as with previous steps. This is shown in Table

16. In many cases, it may no longer be possible to determine the quantity of energy after it has been converted to another form. In these cases, the energy content may be substituted for a volume, if available. Again, appropriately estimated values may be used.

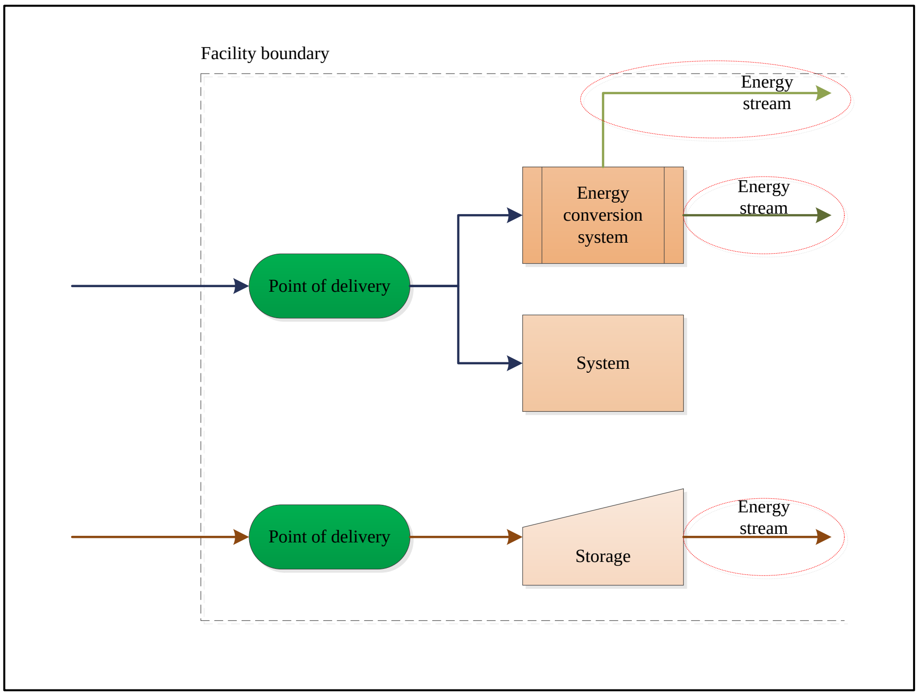

Figure 36: Step 3 – determine the points where energy carriers exit systems

Table 16: Summary of results of Step 3

Energy carrier	Minimum number of meters required	Total annual energy	Total annual cost of energy	Point of origin
E.g. 350 kPa Compressed air	1	50 million CFM	R10 million	System A1 (Compressor plant)
E.g. Coal	1	4 000 TJ	R111 million	Storage A1 (Coal stockpile)

Step 4: System entry points

The next step is following each of the energy carriers identified in Step 3 to the next system. This process is shown in Figure 37. It is important to note points where energy carriers may branch off and travel to multiple systems. The results are again tabulated, as shown in Table 17.

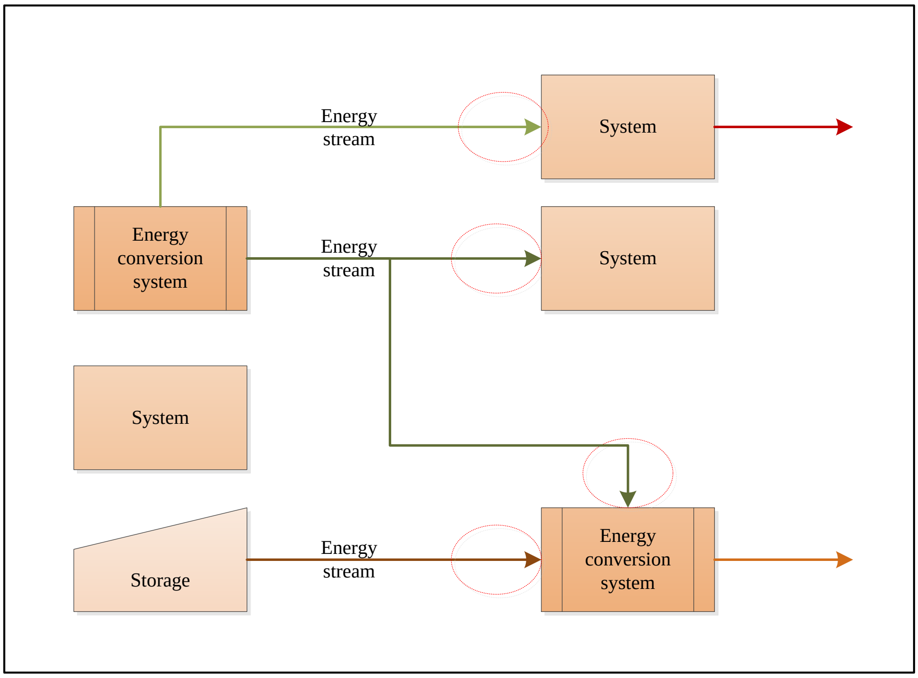

Figure 37: Step 4 – follow energy carriers to the next system

Table 17: Summary of results from Step 4

Energy carrier	Minimum number of meters required	Total annual energy	Total annual cost of energy	Point of origin	Destination point
E.g. 350 kPa Compressed air	1	700 000 CFM	R248 800	System A1 (Compressor plant)	System B1 (Blast furnace)
E.g. Coal	1	4 000 TJ	R111 million	Storage A1 (Coal stockpile)	System A2 (Coal mill)

Repetition of Step 3 and Step 4

For each of the destination points, Step 3 is completed again. Following this, Step 4 is completed again. This process continues until it is no longer possible to perform Step 3 without repeating an energy stream. In this way, the energy into and out of systems can be comprehensively identified. This is shown in Figure 38, with the results tabulated in Table 18.

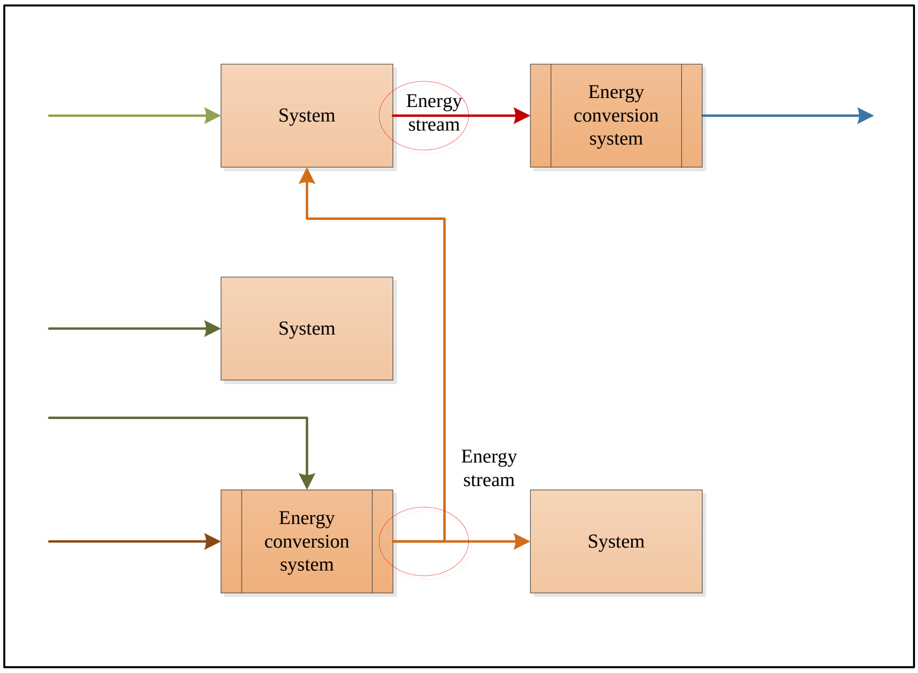

Figure 38: Next iteration of Step 3 – determine where energy carriers exit systems

Table 18: Summary of results from second iteration of Step 3

Energy carrier	Minimum number of meters required	Total annual energy	Total annual cost of energy	Point of origin
E.g. Coal	1	4 000 TJ	R111 000	System A2 (Coal mill)
E.g. Blast furnace gas	1	1 000 TJ	R28 million	System B1 (Blast furnace)

It is theoretically possible that a captive energy source may exist within the facility boundaries. This may occur where an energy carrier raw material is extracted within the facility and not transferred across the facility boundary. If such an instance occurs, the point of extraction of the raw material should be considered a starting point for Step 1, and the process completed again. This is demonstrated in Figure 39.

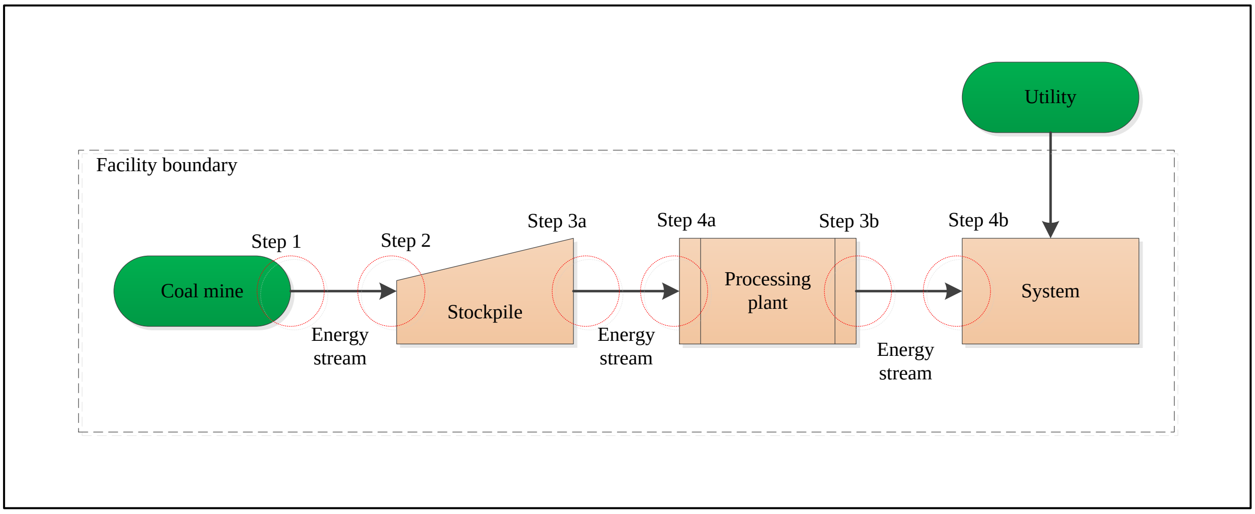

Figure 39: Methodology applied to captive energy sources

After the energy carrier insert and outlet points to every system have been determined, the results of the process can be tabulated. This is shown in Table 19.

Table 19: Summary of results of energy carrier audit process

Energy carrier	Minimum number of meters required	Total annual energy	Total annual cost of energy	Point of origin	Point of entry
E.g. Electricity	4	3 600 TJ	R700 million		
E.g. Coal	1	4 000 TJ	R111 million		
E.g. Electricity	2	800 TJ	R156 million	Utility	
E.g. Coal	1	4 000 TJ	R111 million	Supplier	
E.g. 350 kPa Compressed air	1	50 million CFM	R10 million	System A1 (Compressor plant)	
E.g. Coal	1	4 000 TJ	R111 million	Storage A1 (Coal stockpile)	
E.g. 350 kPa Compressed air	1	700 000 CFM	R228 800	System A1 (Compressor plant)	System B1 (Blast furnace)
E.g. Coal powder	1	4 000 TJ	R111 million	Storage A1 (Coal stockpile)	System A2 (Coal mill)
E.g. Coal powder	1	4 000 TJ	R111 million	System A2 (Coal mill)	
E.g. Blast furnace gas	1	1 000 TJ	R28 million	System B1 (Blast furnace)	

Step 5: Ordering of measurement points

The next step is ordering the results in descending order of annual energy cost. For each energy carrier stream, the number of meters required, and type of carrier should be used to determine the cost of installing measurement devices. This cost should include the total cost of installation, including network communication and labour. The cost of calibration and maintenance of the measurement devices should also be determined.

By using the reported lower saving estimate of 5% [16], [43], an approximate cost saving can be determined. This cost saving should be compared with the implementation costs to determine a payback period for the installation of metering. It may be necessary to include the costs of implementing analysis and feedback systems, as will be discussed later, as well.

Measurement devices should now be prioritised in descending order and in accordance with legislative requirements. Ideally, the entire energy value chain should be measured at system level. This option may however be prohibitively expensive. In these cases, measurement of each energy stream at either the origin or entry point should at least be prioritised.

It should be noted however that for certain energy carriers, significant losses may occur during transfer. This is especially true for compressed air, where leaks can waste from 10% to 50% of generated compressed air [96], [97]. Electric losses in a small high-voltage distribution network are often not significant enough to warrant metering a single stream at both ends. However, with electricity, there are often multiple points of insertion for a single point of origin. If this is the case, the origin and the largest points of insertion should be measured.

It is necessary to consider the direction of energy flow in energy carrier streams. In most cases, energy flows from a supplier towards end users in one direction. However, in some industrial sites, energy streams are arranged between end users allowing energy to travel between them. An example of this is a compressed air line that may run between two plants, while each plant also has a connection to the main distribution line. In these cases, it will be necessary to apply meters that can measure energy flowing in both directions. This is illustrated in Figure 40.

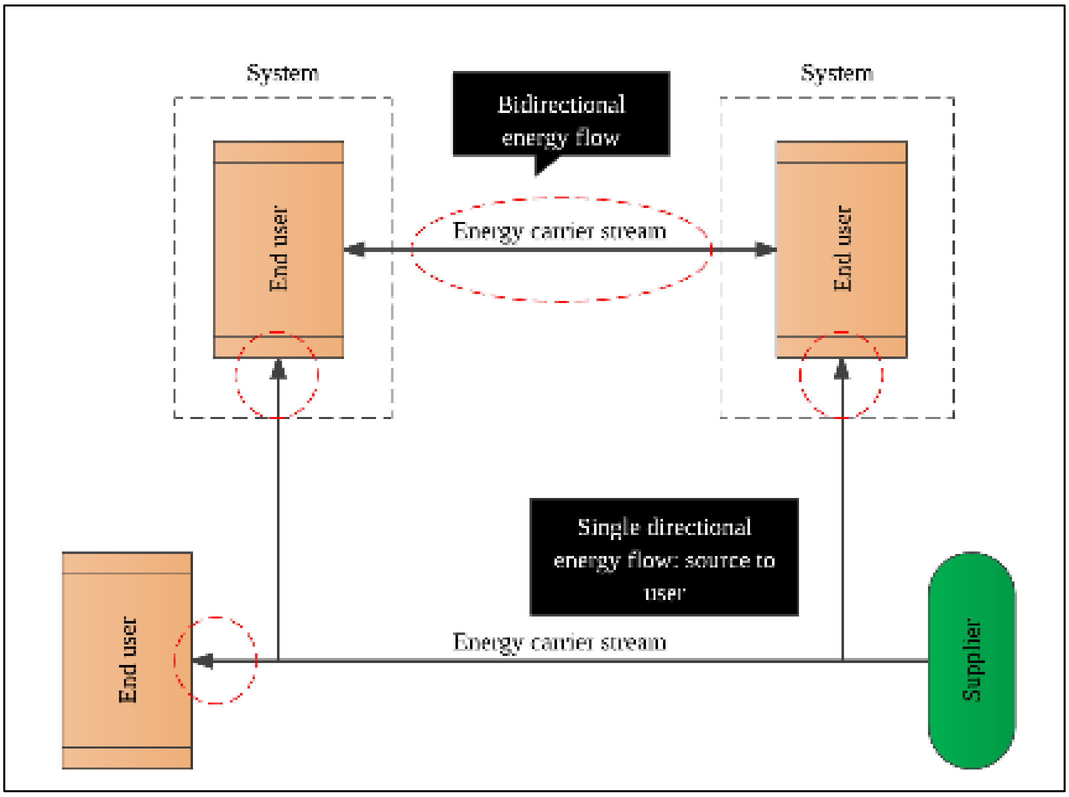

Figure 40: Illustration of energy carriers flowing between end users

For each node that will be metered, it is necessary to identify the environmental and other factors driving energy consumption. In many cases, measurements will already be in place for process control and accounting. However, where they are not, additional measurement devices will be required.

Evaluation of results

After the measurement points have been identified, available meters in the facility must be identified. Those meters that can satisfy the requirements of the defined scope must be identified. Due to multiple meters potentially being available on each energy carrier stream, it may be that more than one meter can satisfy the requirements. After existing meters have been identified, the methodology for metering quality must be applied. A list must also be made of measurement points where no existing meters are in place.

3.3.3 Part B: Evaluating metering quality

Appropriate metering quality will result in verified energy data that can be used for operational energy management. To achieve this, energy carriers must be measured and analysed appropriately. The basic methodology is shown in Figure 41.

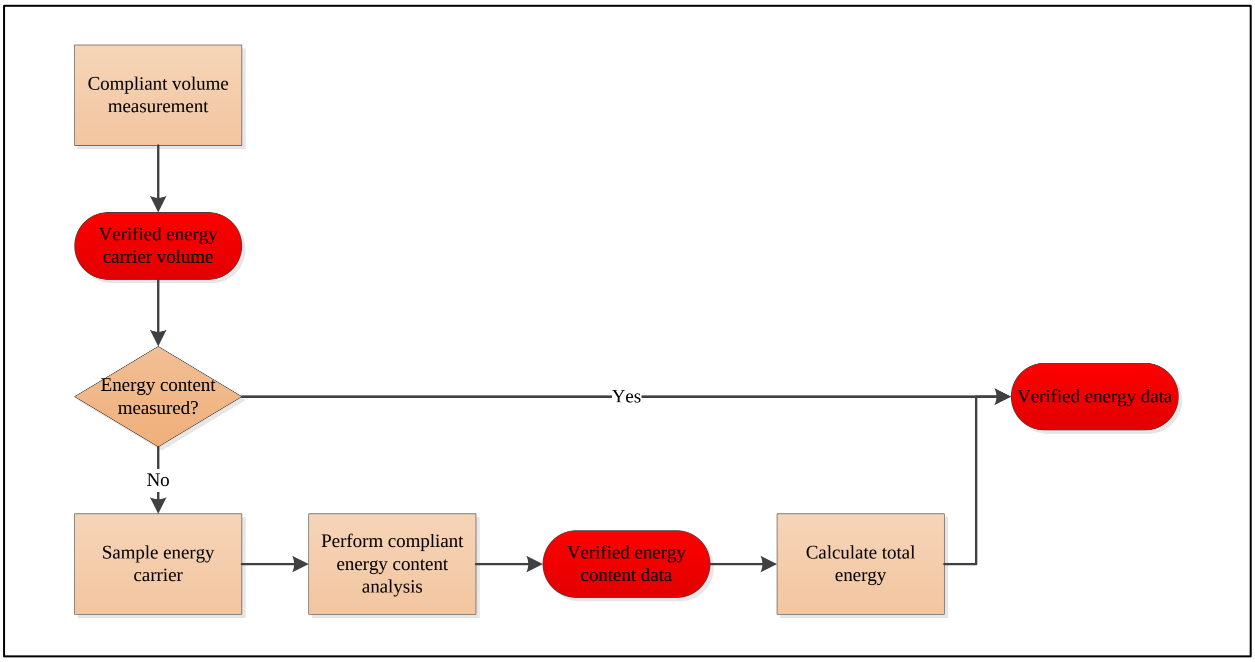

Figure 41: Basic methodology for metering quality

As shown in the figure, the first step is measuring energy carriers with a SANS 50010 compliant device to provide verified energy carrier data. Where necessary, the energy carrier must be sampled as well, and an analysis conducted. This analysis must also be compliant with SANS 50010. This means that the analysis must be performed by a suitably accredited facility with calibrated measurement equipment. This will result in a value of energy content per unit of energy carrier. By combining the energy carrier measurement data with the energy content per carrier unit, the verified energy data can be calculated.

Measurement

In many cases, there are multiple meters in an energy stream. Starting with the meter closest to the origin or insertion point, the process shown in Figure 42 should be followed. The meter must be evaluated to determine whether it complies with SANS 50010. If it does, it can be used as a measuring point. If not, the next meter in the chain must be evaluated.

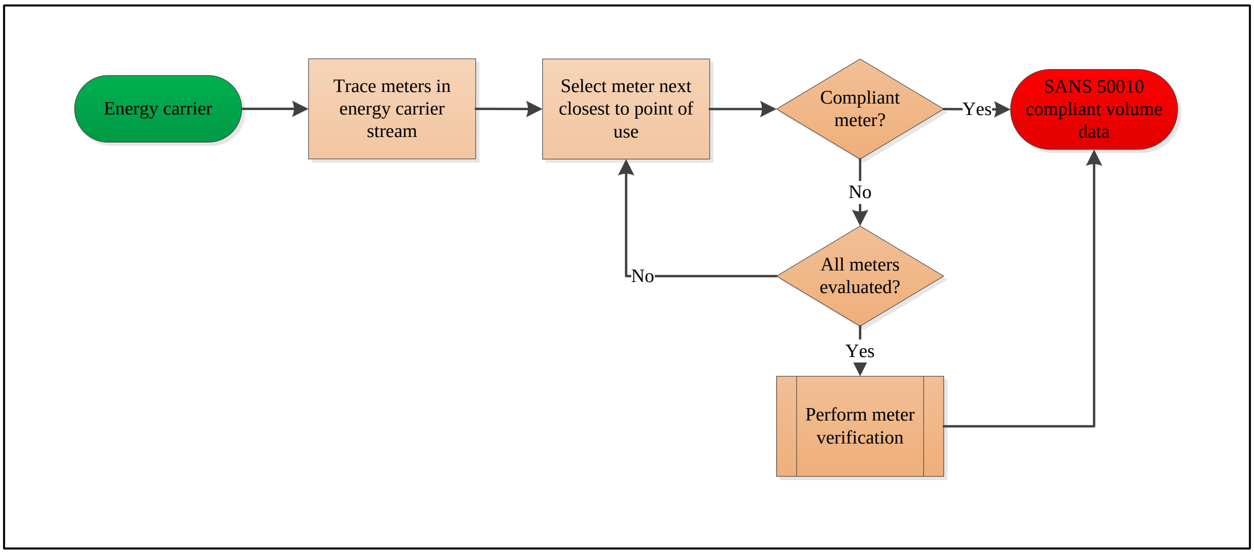

Figure 42: Process for selecting measurement points

Energy content

Electricity is measured in terms of energy content, and therefore does not require further analysis. In certain cases, when energy carriers are purchased, the energy content is included in the invoice. This is often the case with natural gas. Where energy content is provided in the invoice or is linked to a term of supply where there is very little room for variation, continuous or real-time analysis should not be necessary.

Other fuels are purchased according to quantity, such as paraffin, coal and diesel. In these cases, an analysis of the energy content will be required. This is because the calorific value of some of the fuels can vary depending on source.

A methodology for determining the content of the energy carriers being considered is shown in Figure 43. An analysis is required for each energy carrier where the energy content cannot be measured directly. The results of the analysis conducted by the supplier may also be used if an on-site analysis is not feasible.

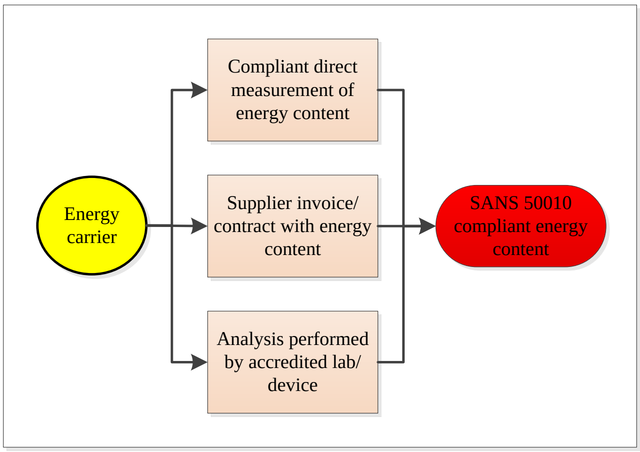

Figure 43: Analysis methodology for achieving SANS 50010-compliant energy content data and verified CO_2e[11] data

Evaluation of results

After applying Part B of the methodology, a list of measurement points has been developed where metering scope and quality are sufficient for operational energy management. Points where meters are available but not of suitable quality must be identified and listed. These points, in conjunction with those identified in Part A, must be evaluated. By comparing this information with the information developed in Part A regarding the value of each energy stream, the compliant metering for implementation at that point can now be determined.

3.3.4 Part C: Energy data management

From the review of industry, a clear problem can be identified regarding energy data in operational energy management – the data is not available where it is needed for analysis and feedback. The methodology will now present a solution to this problem. A high-level overview of the methodology is provided in Figure 44.

The data management problems found in industry can be grouped into two areas. The first problem is that energy data is rarely checked for integrity, and these checks are usually passive. This means that measurement data can be incorrect for a long period before any problems are found. Secondly,

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[11] CO_2e refers to Carbon dioxide equivalent emissions. This is the equivalent emissions that has the same greenhouse gas effect as 1 tonne of carbon dioxide.

energy data is often located on data islands that are not easily accessible. This means that the data may not be available where it is required for operational energy management.

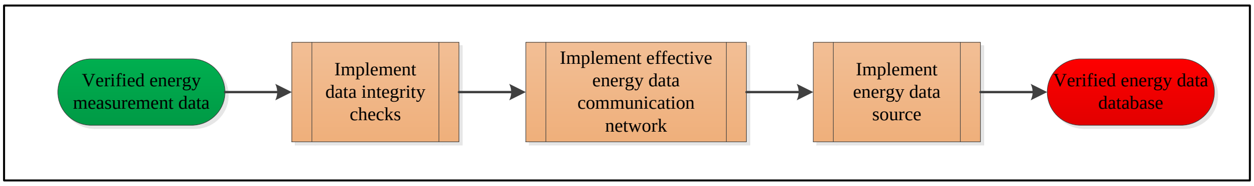

Figure 44: Overview of data management methodology

Energy data integrity

The next step of energy data management is to perform integrity checking. These integrity checks should not be passive, meaning that they must not rely on a user reviewing the data before an error is identified. Thus, an automated integrity checking solution is recommended. This can be implemented as a front-end of many databases.

The purpose of integrity checking should not be to correct errors, as this will usually not be possible. Instead, the integrity checking module should serve to detect and inform personnel when an error has occurred. The basic steps of this process are firstly to identify common data integrity problems experienced by the facility. The next step is developing integrity checks that can detect these errors when data is received. These integrity checks must be implemented in the system. Ideally, the system should also be capable of alerting personnel when non-conforming data is detected. This is described in Figure 45.

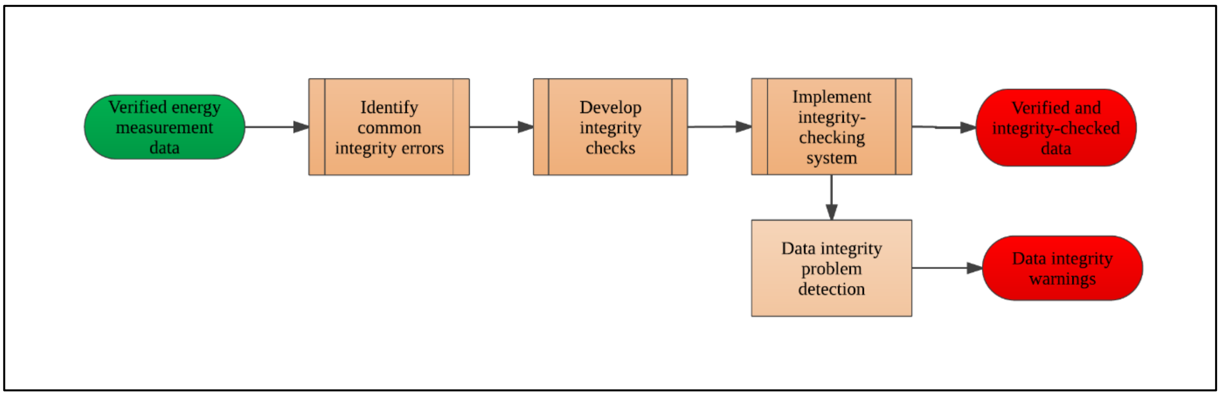

Figure 45: Overview of data integrity methodology

There are three errors common to energy data communication networks in South Africa. The first is when metering devices experience problems and start transmitting zero values. The second typically occurs when an incremental meter reaches its maximum value and reverts to zero, resulting in a sudden large spike. Finally, when communication problems occur, energy data received may read the same value for an extended period when a value has been latched. The typical profiles of data showing these types of error are shown in Figure 46.

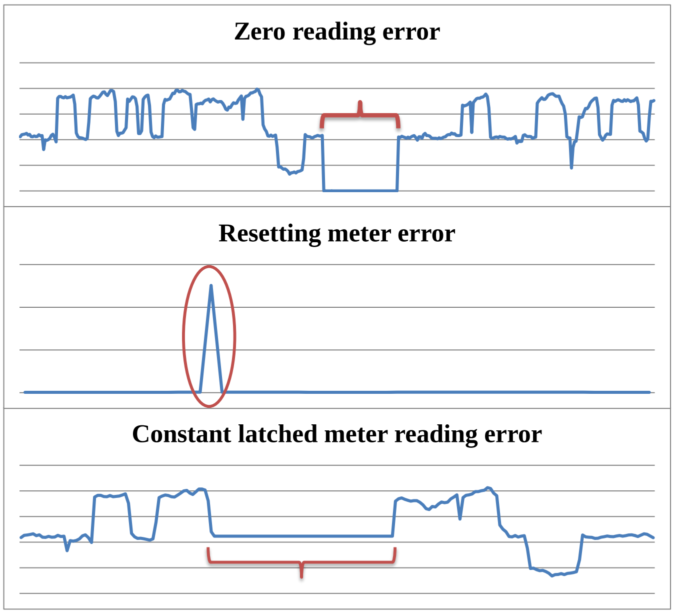

Figure 46: Profiles of common energy data problems

There are typical checks that can be applied to detect these types of error. First, each energy data tag should be checked for variance. In industrial applications, it is very unlikely that energy consumption reaches absolute zero – in most cases, a small fractional load remains as part of losses in the system. Second, each tag should have an expected minimum and maximum value. Typically, the maximum will be slightly more than the maximum load that the system is expected to draw, or the installed capacity of the components. Finally, additional checks should be implemented based on the specific situation found on the plant.

Energy data communication network

The first step deciding which points on the facility’s data management network will be used to perform analysis and feedback. This can be a single node in a small facility, but will most likely be a distributed set of nodes.

The second step ensuring that the correct energy metering data reaches the appointed nodes in timely intervals. This will require considerations discussed in Section 3.5.3 before a decision can be made, but will usually mean that real-time data should reach control rooms while data can reach the main feedback node in less regular intervals.

This process is shown in Figure 47. As the figure shows, data communication to operators should be real time or near real time. Data used for summary analysis and reporting can be transferred in intervals. In certain cases, it may be suitable for data metering to transfer data in intervals rather than real time. This will however only be the case where information from these devices will not lead to quick actions being taken. For example, coal quantities being loaded onto a stockpile will likely not need to be used for real-time feedback. It is important that feedback to control room operators be considered when deciding where operational energy management is considered.

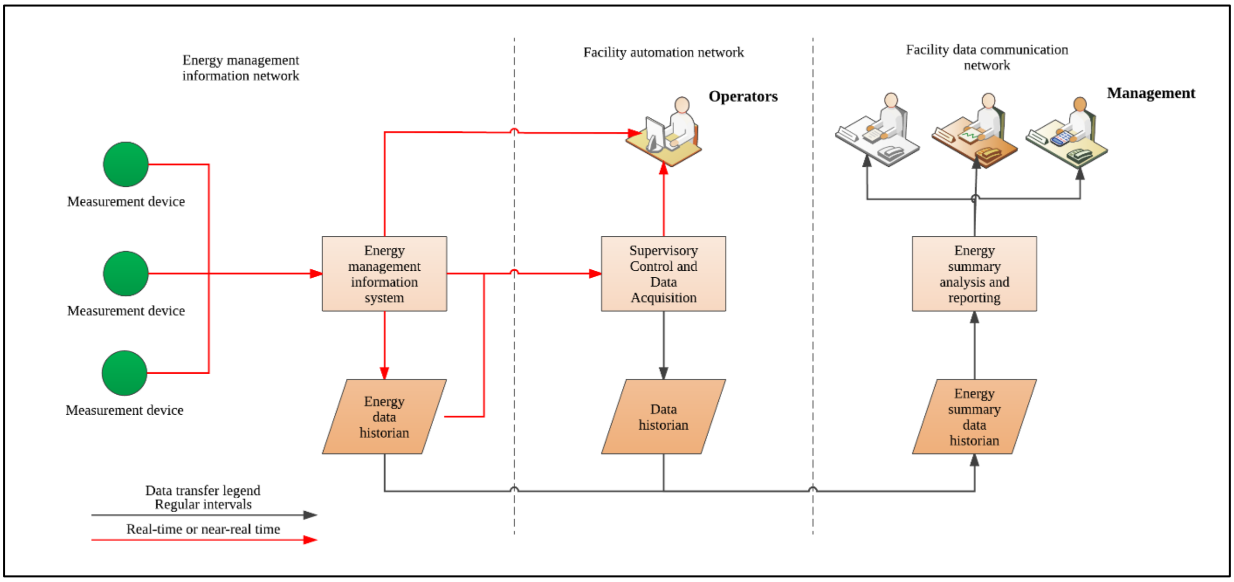

Figure 47: Data communication layout for operational energy management

For each measurement device, the data resolution must be considered. For most energy carriers, a high resolution is necessary due to quick control changes that can take place on such systems. At minimum, energy carrier data should be available in two-minute intervals. For coal, this may not always be necessary.

3.3.5 Data source

As discussed in the previous chapter, existing feedback methodologies applied in industry have a problem regarding which data sources are used. In many cases, a data source is chosen due to ease of access, how easily it can be found, or simply because it is the only one the employee is aware of. This can result in incongruent feedback.

It is therefore necessary that a single data source be identified and used for energy data. All energy performance analyses and feedback should be based on this data source. This will ensure that feedback is congruent across time and will not be liable to errors. This concept is shown in Figure 48.

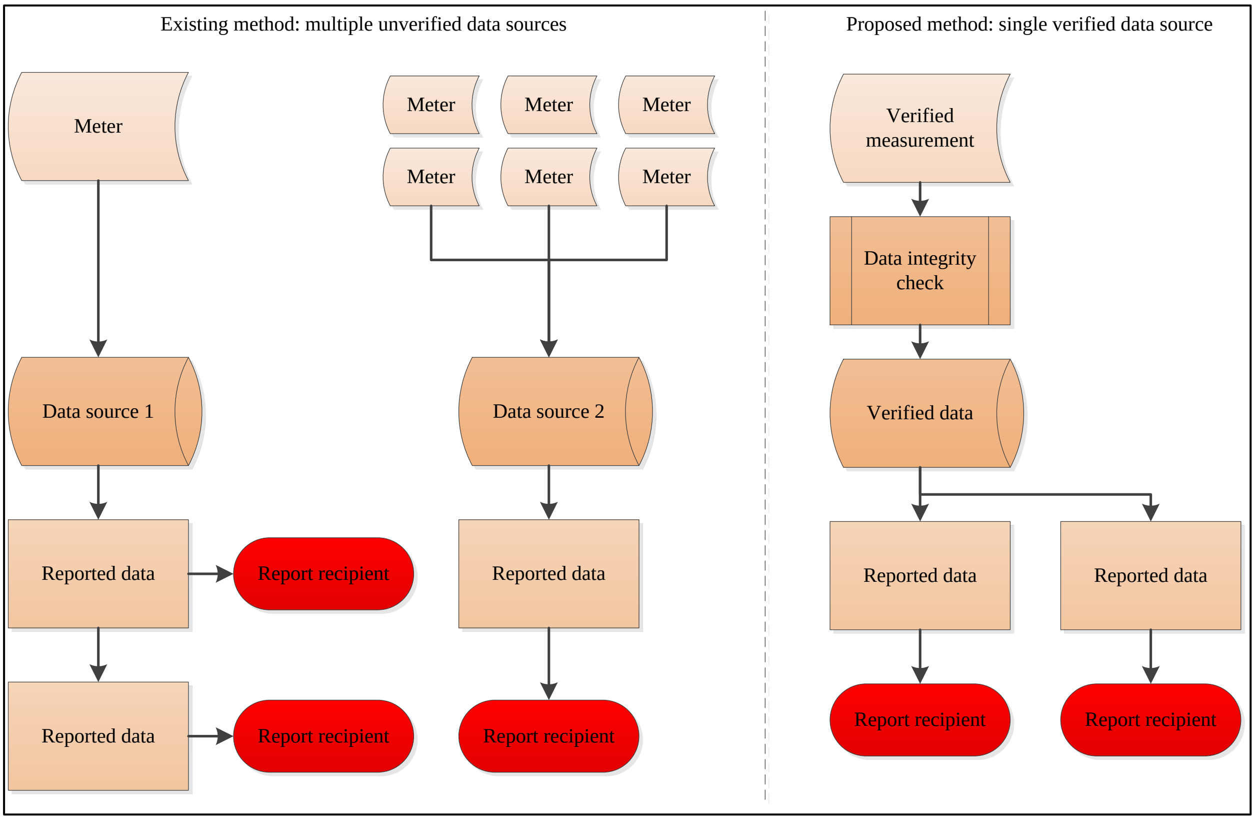

Figure 48: Structure for feedback data source

Following this step, both the measurement and data management of energy management data will be in place. The next step in the process is to use the data, as well as other information regarding each system, to develop an indication of the performance of the system. This analysis phase will be discussed in the next section.

3.4 Development of new methodology for energy performance analysis

3.4.1 Overview

In this section, a method will be developed for analysing energy performance for operational energy management purposes. As operational energy management is practised in near real time, this means that energy performance information must be available in this time frame. Thus, energy performance must be analysed in real time; longer term analyses will not be suitable.

In order to provide energy performance information suitable for operational energy management, a method must be developed to perform the analysis in the short term. The analysis should use available information and provide an accurate estimation of what energy consumption should be under the prevailing circumstances. This information, when compared with actual consumption, will provide information regarding actual energy performance.

There are three parts to the development of this methodology. First, it will be necessary to evaluate which energy drivers act on the different systems at the facility. A systematic method similar to that developed in the previous section is presented to do this. This will allow the user to determine which systems act as energy drivers on other systems.

Next, for each system, the different energy drivers acting on it will be investigated. These include other systems, but also other drivers such as ambient conditions. This will allow the user to identify the major energy drivers that act on each system, which will need to be predicted and monitored for determining energy performance.

Finally, two methods are proposed for modelling system energy consumption. The first, and more accurate method, requires a model to be developed for each system that mathematically relates the actions of energy drivers to the system’s energy consumption. However, in many industrial facilities, this option may not be possible or quickly implementable. As such, an alternative methodology is proposed using historical data. Figure 49 shows the basic process.

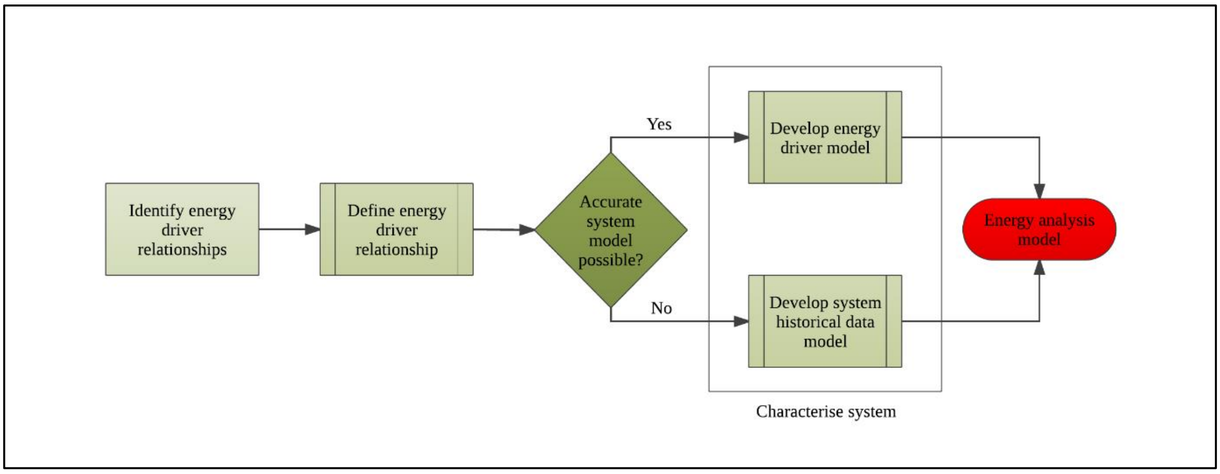

Figure 49: Basic process for data analysis

3.4.2 Part A: Identifying energy driver relationships

The process for identifying energy drivers will be described in this section. This process is similar to that followed in Section 3.3.2 to identify locations for metering except for two differences. Firstly, this process will proceed from the output of the industrial facility and work backward towards the input. This is done because the purpose of the process is to determine causality. More simply put, the purpose for the facility is to provide a certain output (for example, producing cement, gold or steel). The energy drivers can be determined by beginning with this output and systematically working backward throughout the facility.

The second major difference is that the process focuses on tracking the input streams, or energy driver, streams between the different systems. For a system producing an end product, certain inputs are required from other systems. These inputs include raw materials, such a cement clinker, or services, such as compressed air. The system can therefore be said to be driving the demand for that specific input. Through this process, a network of energy drivers can be developed, allowing the user to determine the energy drivers for each component.

There are several potential starting points for this process. The process will need to be repeated with each end point in mind to ensure that the entire energy driver network is developed effectively. This is primarily because some systems may not be linked to production through another system. For example, many heating, ventilation and air-conditioning (HVAC) systems on underground mines are in place to ensure safety for the personnel underground.

The first step is identifying the end products that are delivered across the facility boundary. Each of these end products can be linked to the system that produces them. In some cases, multiple end products can be linked to the same system. In such a case, this must be identified and noted. This process is shown in Figure 50. It is important to note that in many cases there will be a buffer between the final production system and the sale of products. These buffers can either be treated as part of the production system (for simplicity), or as separate entities (for improved accuracy). An example of this is a product stockpile in a factory.

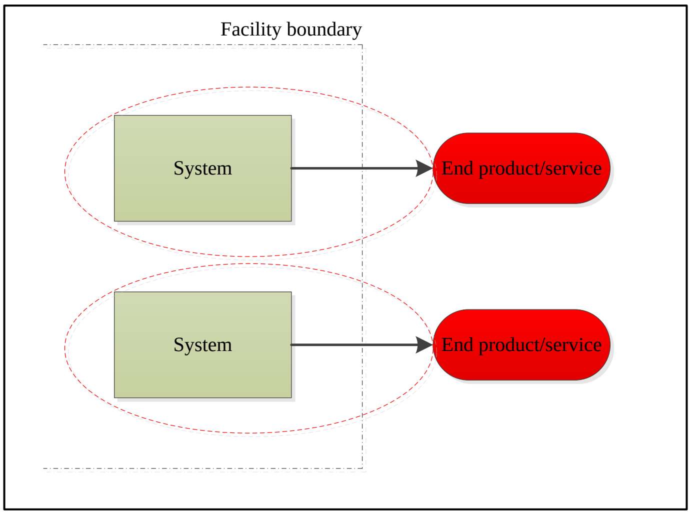

Figure 50: Step 1 – identify end products and systems

The second step in the process is identifying the systems that supply those identified in Step 1 with a service or a product. Each of these systems are identified and noted, as well as the type of service or product they deliver. Again, there may be a buffer between systems where products are involved. This process is illustrated in Figure 51.

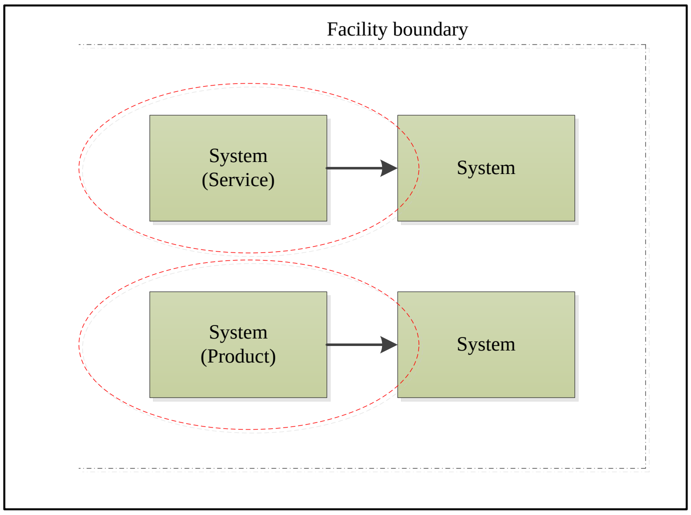

Figure 51: Step 2 – identify next layer of systems

For each of the systems identified, the process is repeated. Step 2 repeats until the next step in the process again crosses the facility boundary. At this point, a basic network of drivers will have been developed. This is shown in Figure 52.

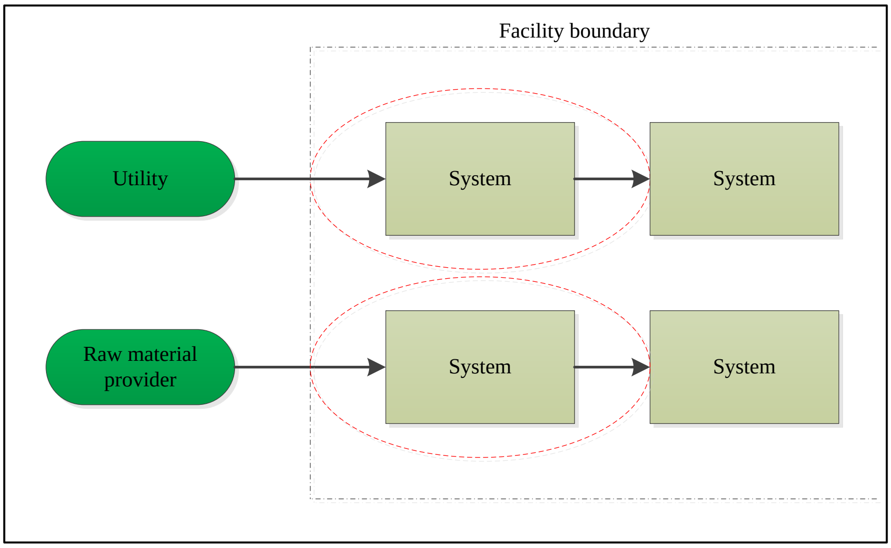

Figure 52: Step 3 – continue process until inputs cross facility boundary

Before continuing to the next phase it is important to review the energy-using systems and determine if any systems have not been included in the network yet. If so, it will be necessary to identify the end point for that system's service and begin working backward as already described.

3.4.3 Part B: Defining energy driver relationships

The next phase in the process is defining the relationship between each system and the systems it acts on as a driver toward. Specifically, it must be determined whether there is an energy driver relationship between the two systems.

Figure 53 shows the basic process. Each system should be evaluated individually. The next step is identifying whether the system is significant to energy consumption on the premises, which should be evaluated in detail. If the system must be included, detailed information is collected. This detailed information includes:

- SEUs (such as installed electric motors),
- Existing budgets,
- Configuration and layout of system,
- Energy drivers acting on the system, and
- Planned operational changes and energy efficiency projects.

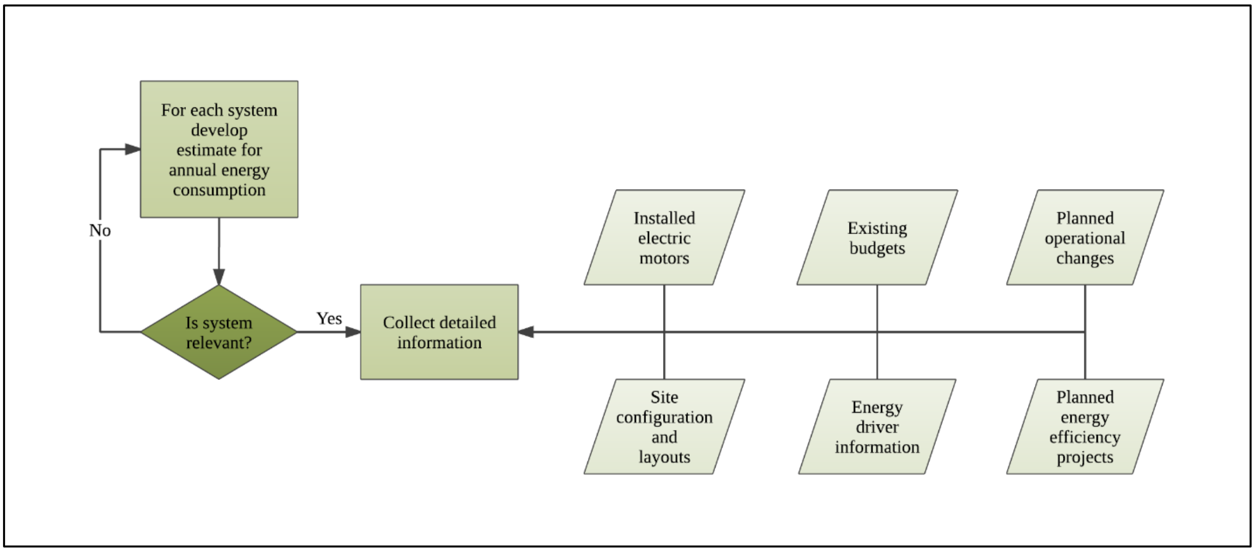

Figure 53: Collect information step

To identify the primary energy driver acting on the system, the question is asked: “Why does this system run?” By answering this question, the primary driver that requires the system to operate can be identified. The next important question is: “Which service does this system need to operate?” This question identifies other systems towards which the system being evaluated acts as an energy driver. However, there are typically several additional energy drivers acting on the system, which will be identified next.

Figure 54 shows the next step in the process. First, the system boundary is identified, and energy carriers crossing the boundary either outward or inward are identified. The primary energy user associated with each energy carrier is identified.

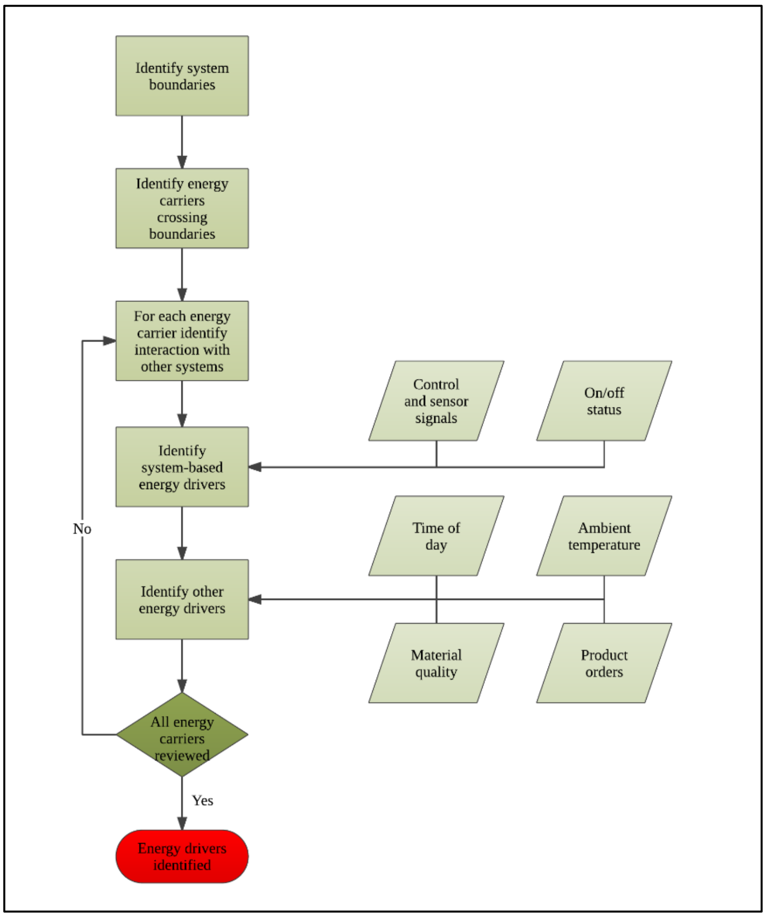

Figure 54: Identify energy drivers

For each energy user, drivers that act on their energy use are identified. This will typically be the demand for a product or service from another system. However, secondary energy drivers must also be identified. These are energy drivers that impact the system, but are not associated with other systems within the facility. A typical example of this is ambient temperature for cooling systems. Ideally, all energy drivers that are not baseload or associated with another system should be identified to such an extent that the profile of energy demand within the system can be estimated accurately.

The energy carriers feeding into the system must be identified and labelled, as shown in Figure 55. The outputs and demand for outputs must also be determined. Table 20 shows several examples of energy-using systems in industry and their related energy drivers.

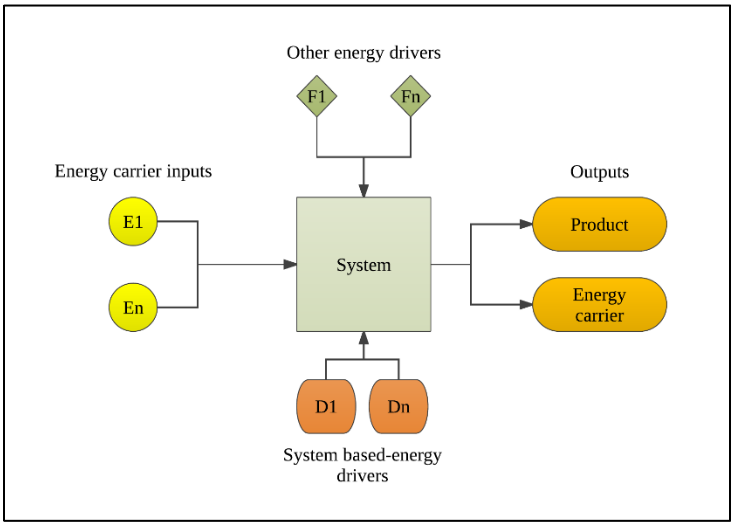

Figure 55: Characterisation of energy-consuming system

Initially, many of the loads acting on the system may be termed unattributed or baseload. However, as the characterisation of the system improves, the drivers for parts of these loads can be identified and modelled. Doing so will improve the effectiveness of the entire energy management system. This process is especially critical if the unattributed use of a system makes up a large proportion of the system's load (i.e. greater than 5% of consumed energy). This is demonstrated in Figure 56. In this graph, the energy drivers that act on the system have been linked to the relevant energy carrier stream. Individual large energy consumers, as well as the role they play on energy consumption within the system, are identified.

Table 20: Example of systems and energy drivers in industry

Industry	Energy carrier	System	Energy driver
Steel plant	Coal	Blast furnace pulverised coal	Blast furnace production rate
	Natural gas	Continuous annealing	Annealing plant production
	Electricity	Sinter plant extraction fan	Sinter plant production
Gold mine	Electricity	Winding	Number of hoists, tonnes hoisted per skip
	Electricity	Compressed air	Ambient atmosphere, air compressed, pressure, compressed air demand
	Electricity	Refrigeration plants	Ambient atmosphere, chilled water demand
Cement plant	Coal	Kiln	Clinker production rate
	Electricity	Raw mill	Raw meal production

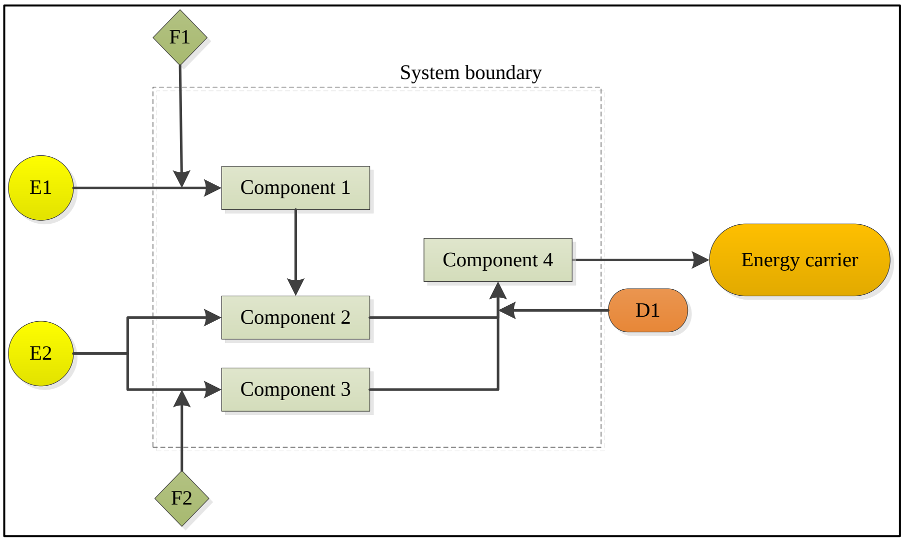

Figure 56: Characterisation improves as understanding of underlying system is improved

3.4.4 Part C: Characterisation

Two options are available for characterising the system and developing an energy performance model. The first is developing a mathematical energy driver model. In this approach, the effect of each component on the system must be modelled and tested. A sufficiently accurate model can then be verified against data from the actual system. Although this is a reasonably accurate approach, it is a more intensive process, more difficult to implement, and may be more expensive due to the requirement to measure energy drivers. In cases where it is not viable to take this approach, an alternative is provided. The alternative methodology uses historical data and metadata to develop an energy performance model.

Energy driver model

Once all system-based and secondary energy drivers have been identified, the system can be characterised. This process is shown in Figure 57. The first step is collecting available historical data for the different energy drivers. In many cases, not all energy drivers may have data available. In this case, the available data should be evaluated. For each energy driver, the relationship between energy consumption and the driver is characterised.

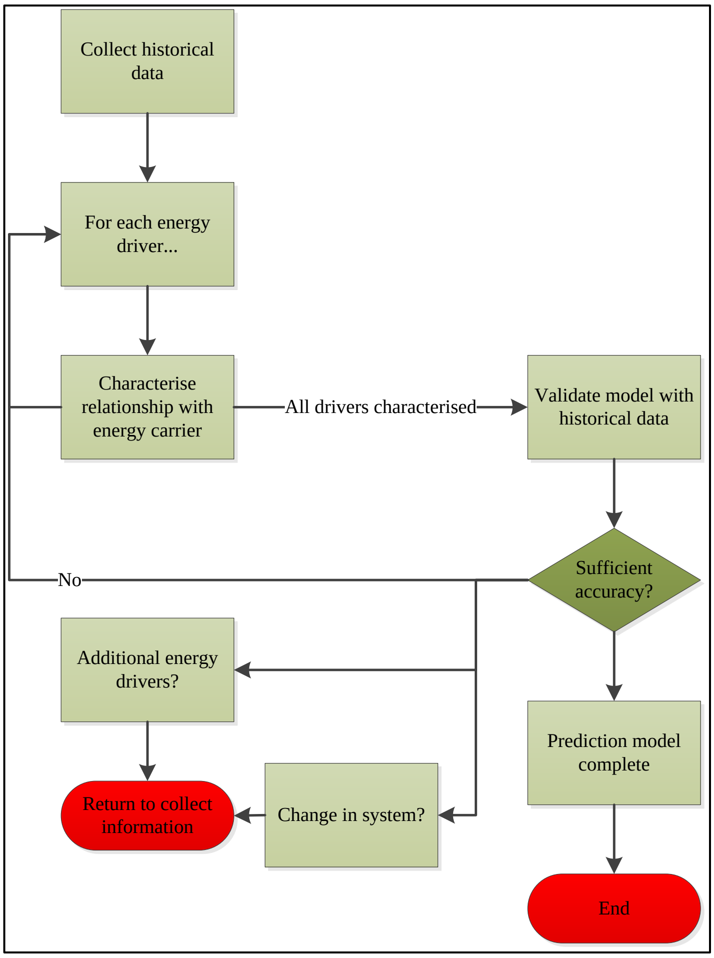

Figure 57: Characterise energy driver relationship

If sufficient information for the system is available, this step can be completed easily. However, in many cases this will not be possible. In this situation, the impact that each driver has on the system should be isolated where possible. This is done by identifying sections in the data where only the driver being considered has changed significantly, while other drivers remain the same. A correlation function can also be used as a less accurate method.

The next step is mathematically characterising the relationship between the demand for outputs, the additional factors and the energy carriers. Equation 3 shows a simple function for the relationship between the energy demand and output from the system.

$$E_{C1}^{t} = F_P \cdot C_P \cdot D_P + F_{S1} \cdot C_{S1} \cdot D_{S1} + B \tag{3}$$

Where:

E_{C1}^{t} is the budget energy consumption for Energy Carrier 1.

F_P is the factor relating the primary energy driver to Energy Carrier 1.

C_P is a constant.

D_P is the primary energy driver or an estimate of the outputs required from the system.

$F_{S1} \cdot C_{S1} \cdot D_{S1}$ relate to the secondary energy driver.

B is a constant base demand.

The total expected energy demand for the system can then be determined by summating the estimate for the different energy carriers, as is shown in Equation 4.

$$E^{t} = E_{C1}^{t} + E_{C2}^{t} + \cdots + E_{Cn}^{t} \tag{4}$$

It is important to note that the relationship between an energy driver and energy carrier might not be linear. In these cases, this non-linear relationship should be built into the model.

It could be unnecessary to investigate and characterise a system to the finest level of detail, and in many cases it may even be counterproductive. Instead, the aim should be to characterise the system until the baseload, operational baseload, and energy drivers accounting for 95% of energy consumption of a SEU are understood. In the case of very small systems, it might not be necessary to set the threshold this high.

Another important consideration is when the historical data reflects a very different usage pattern from the pattern proposed by the energy budget. In these cases, it may be that the system in question is already behaving in an inefficient manner. For example, a compressor that is not being controlled to match the demand on the system will not follow the demand pattern. If this is the case, the energy manager will have to decide whether to adjust the budget accordingly, or to start an intervention.

Historical data model

In certain cases, it might be unsuitable to use the energy driver modelling approach. This will typically be where energy drivers are not measured, and their measurement is not cost effective. This is also common where energy drivers can be measured, but not on a timescale effective for operational energy management. In these and similar cases, it may be necessary to develop a model based on historical data and metadata. This will be described next.

The historical data model is primarily useful for systems where energy performance cannot be effectively modelled, and energy use is expected to follow a step pattern. A typical example is on a deep level mine, where measuring the quantity of rock drilled (a driver of compressed air use) at the stope face would require expensive systems that may reduce production. However, as these drilling shifts occur at roughly the same time of day on all working days, historical data can potentially act as a stand-in for this information.

The basic methodology for developing the historical data model is shown in Figure 58. First, data and information about the system must be collected. This should include historical energy usage data, as well as information about the drivers acting on the system. This process will likely have been completed in the previous phase. The next step is using the data, as well as any metadata available (such as date, time of day, day of week or season), and determining whether there are patterns and correlations with energy data. The correlation between the energy carrier usage and the metadata can be used to estimate the magnitude of the influence of the different historical metadata.

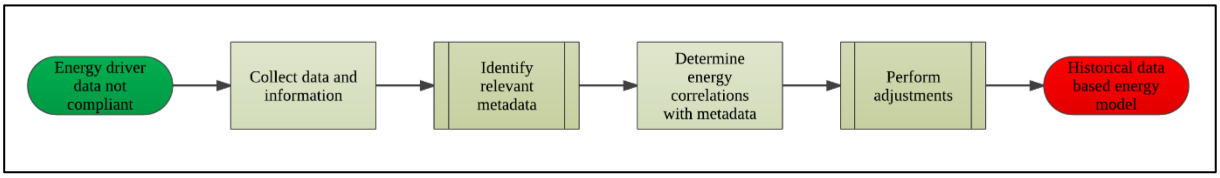

Figure 58: Basic methodology for historical and metadata based model

A model can be developed using this data. The model should use metadata as inputs, and thereby produce estimated energy consumption. It is however important to note that there is a need for a step where adjustments can be made based on changes to energy drivers. This model is reliant on energy drivers remaining mostly the same. Whenever a significant change is made resulting in changes to energy drivers, this must be incorporated. A typical example is a change in the type and mixture of raw materials used in a cement plant, or the number of levels operational on a deep level mine.

3.5 New energy feedback strategy

3.5.1 Overview

In the final section of the methodology development, the process for developing and implementing operational energy management feedback will be shown. For operational energy management, there are several criteria that are important to ensure its effectiveness. Paramount among these is to ensure that the correct feedback reaches the correct responsible people capable of acting on it in a timely manner.

This methodology will be divided into two parts. Firstly, a method will be shown to evaluate where feedback is required, and what the scope of that feedback will be. This will ensure that stakeholders who require feedback are accurately identified so that feedback can be developed for them. The second part will focus on the criteria and considerations for each individual piece of feedback developed. This basic process is shown in Figure 59.

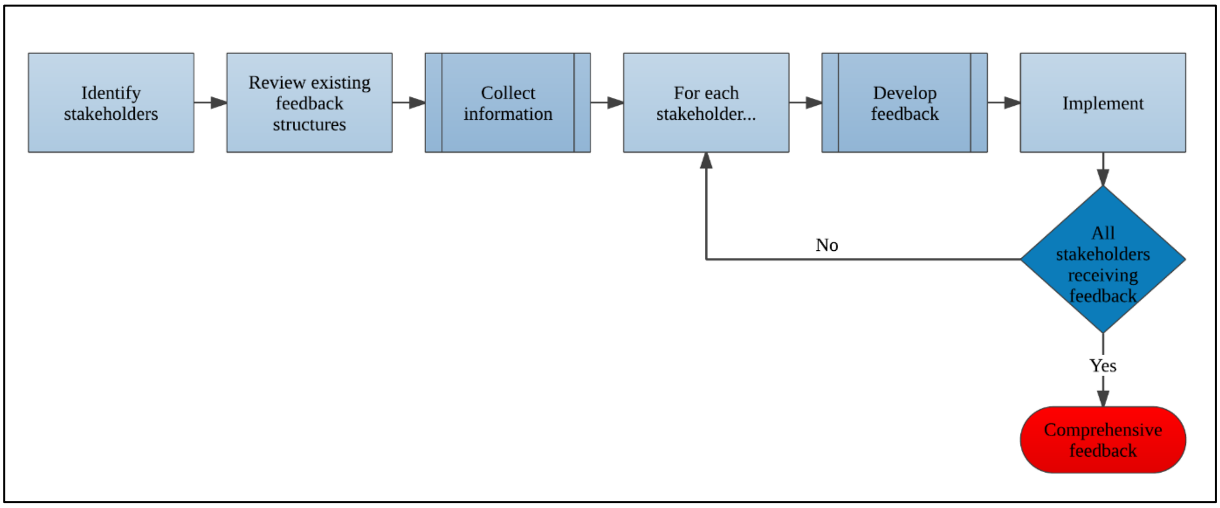

Figure 59: Basic methodology for feedback development

3.5.2 Identifying stakeholders for feedback

The first phase of implementing feedback is developing a comprehensive list of stakeholders requiring feedback. As in the previous two sections, this will be done with a systematic process. The basic process that will be followed is shown in Figure 60. First, a list of systems identified for operational energy management must be drawn up. This list should include only systems that have been identified as significant (as in prior sections) and for which data is available. However, in certain cases, energy managers may elect to include all systems for which any kind of data is available, even though analysis and modelling of the system has not been implemented yet.

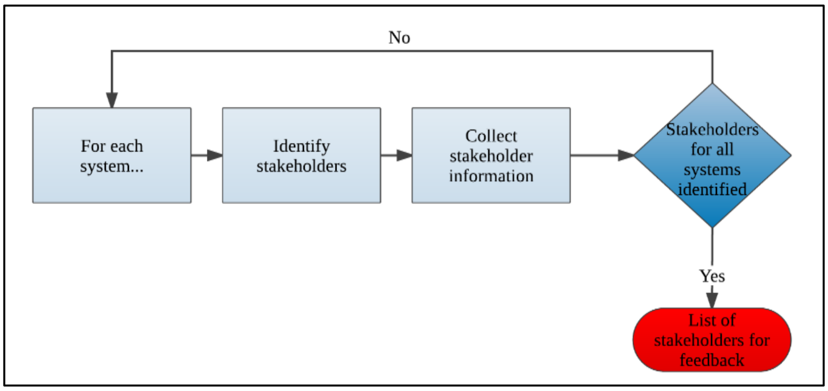

Figure 60: Basic process for stakeholder identification

The next step is identifying the stakeholders who require feedback on the respective system. This step will be highly specific to the organisational structure. However, an example structure present in an industrial company is shown in Figure 61. As the figure shows, energy-using systems are controlled by operators. Operational personnel report to departmental managers, who in turn report to plant management. For operational energy management, feedback begins at the level of operators, and escalates up the hierarchy.

It is important at this point to note that many personnel at higher levels of the hierarchy will have a stake in multiple systems. This should be noted at this point as it may be possible to synthesize and integrate feedback to these stakeholders. Other information that should be recorded for each stakeholder is the degrees of separation between him and underlying systems. This will assist in evaluating the makeup of feedback to the individual stakeholder.

The next step is identifying the relevant operators for each system. As operators often work in shifts, it is sufficient to identify the relevant control room. In some cases, multiple systems may be controlled by a single individual operator position. However, these cases must still be listed individually. An example of this is shown in Table 21.

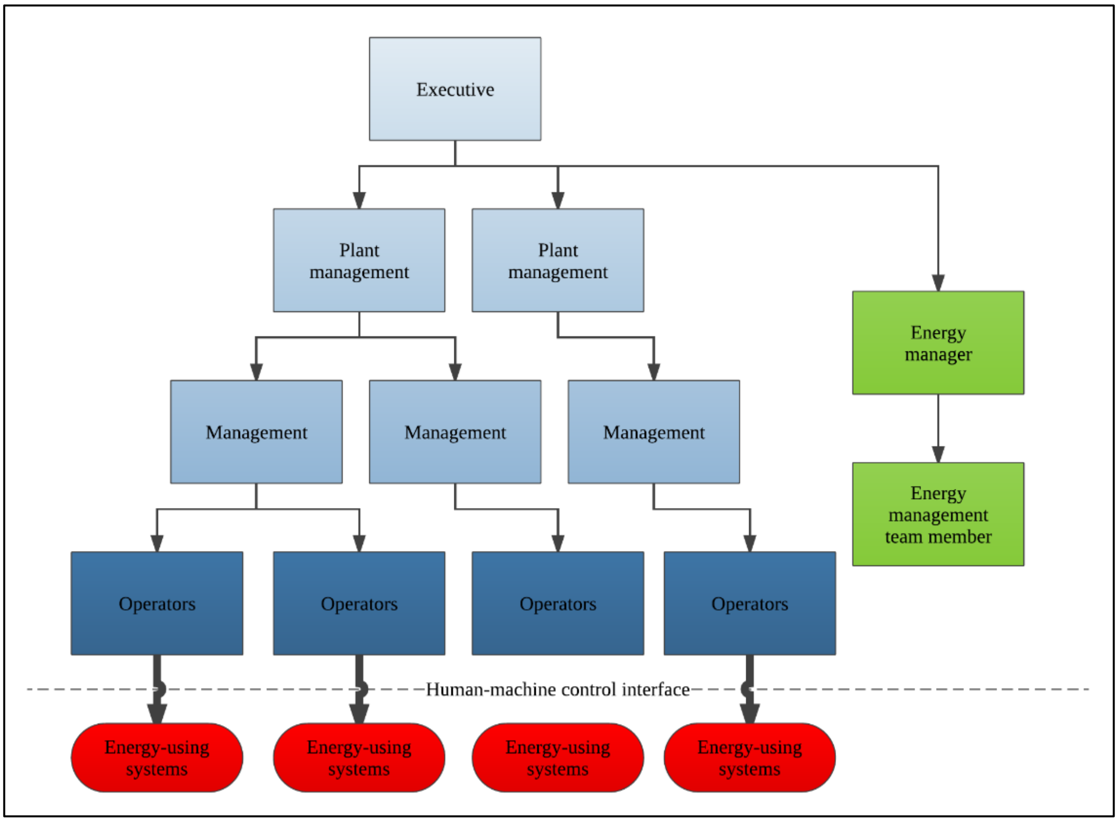

Figure 61: Typical hierarchy of industrial companies

Table 21: Examples of systems and operators in industry

Industry	System	Operator
Mining	Compressed air plant	Central compressor control room
Mining	Dewatering pumps	Shaft control room
Cement	Raw meal grinding	Mill control room
Steel	Boilers	Boiler control room
Steel	Furnace	Furnace control room
Steel	Cold rolling	Rolling control room

Following this, the relevant managers, plant managers and other personnel in the hierarchy must be identified. Each level must be identified between the operators and the highest level at which reporting is done in the company. In many cases, a single position will be responsible for multiple energy-consuming systems. This should be indicated as in Table 22.

Table 22: Examples of systems and operators in industry

Industry	System	Operator	System manager	Division manager	Executive
Mining	Compressed air plant	Central compressor control room	Compressor manager	Services manager	Mine general manager
Mining	Dewatering pumps	Shaft control room	Pumps manager	Services manager	Mine general manager
Cement	Raw meal grinding	Mills control room	Production engineer	Production manager	Plant general manager
Steel	Boilers	Boiler control room	Air, steam and power manager	Services and engineering manager	Plant general manager
Steel	Furnace	Furnace control room	Production engineer	Rolling manager	Plant general manager
Steel	Cold rolling	Rolling control room	Production engineer	Rolling manager	Plant general manager

3.5.3 Developing feedback

The next part of the process is developing individual feedback for each relevant stakeholder. This process is shown in Figure 62. The first step of this process is determining for which systems each stakeholder requires feedback. In addition to this, the stakeholder's ability to control the underlying system must be evaluated, and the method of control for operators. Operator control means direct control, while executives set policy and do not control machines directly. Feedback is then developed for each stakeholder based on the criteria described below.

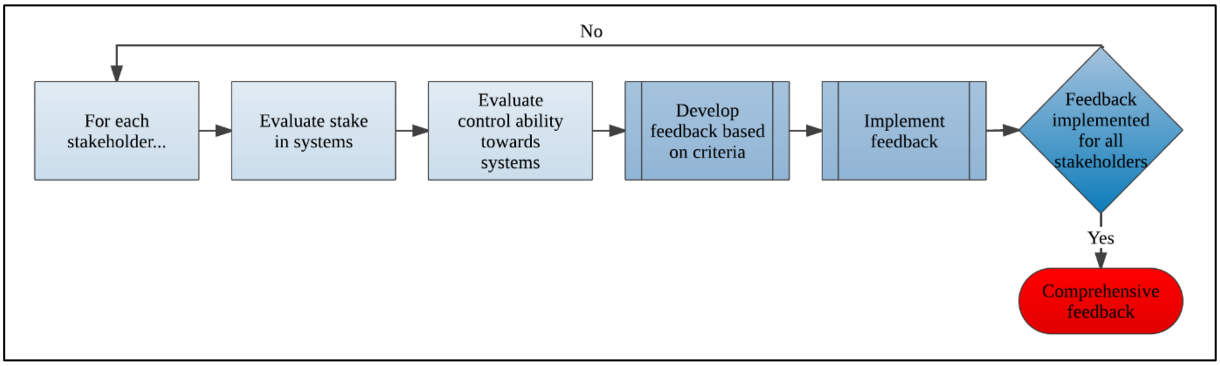

Figure 62: Basic process for developing feedback for each stakeholder

Reporting has many different purposes such as evaluating performance, providing assistance in identifying problems, reporting to public, providing information and budgeting. Each report should ideally serve only one or two purposes to be maximally effective.

Individual feedback development based on criteria is a five-step process, as shown in Figure 63. Each step is implemented in sequence. By following this process, the important considerations for feedback are evaluated and considered adequately.

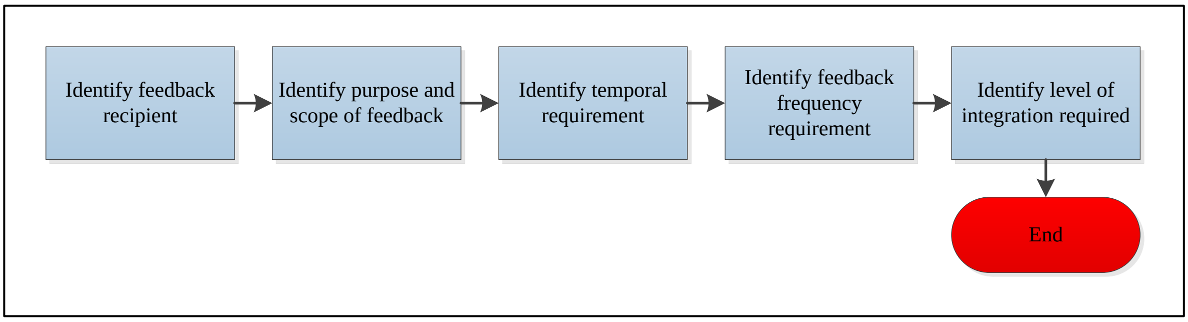

Figure 63: Overview of method for developing feedback

Step 1: Identify recipient

The first step is identifying the recipient of the feedback. At this point, information regarding which systems the stakeholder requires feedback on, as well as the degrees of separation between the recipient and the system, should be identified. This information will assist in decision-making regarding all further steps in the process. Generally, the larger the number of systems the stakeholder is responsible for, the more refined the requirements for feedback are. This means that information should be processed further, resulting in less overall resolution but greater scope.

This is shown in more detail in Figure 64. At operator level, the number of systems the stakeholder is responsible for is very low (typically only one). However, this stakeholder has direct control of the energy performance of the system. As such, when a non-conformity is detected, it is important to know exactly what the cause of the problem is so that it can be rectified. At executive level, however, there is no direct control. Instead, it is important at these higher levels that it is only known that there is a problem. This will allow high-level stakeholders to influence policies and reduce the number of non-conformities.

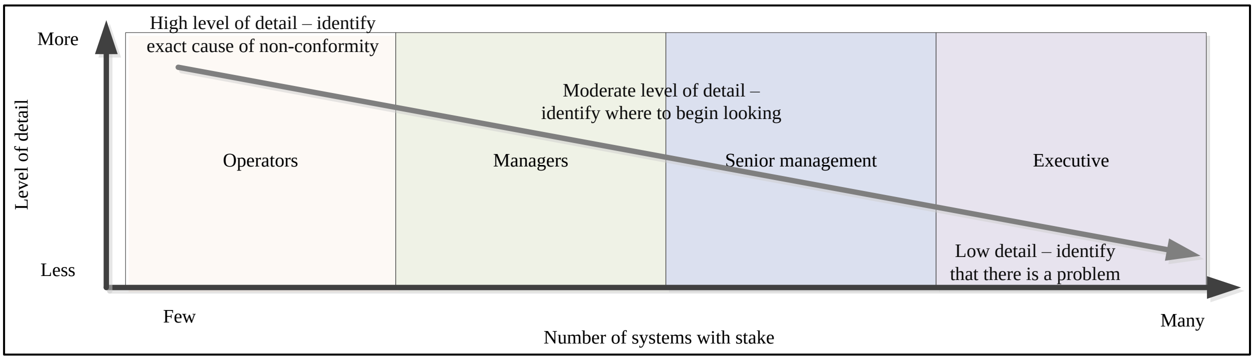

Figure 64: Guideline for feedback based on number of systems and degrees of separation

Step 2: Identify feedback purpose and scope

The purpose and scope of feedback are dependent on the recipient level. At the operational level, the intention of feedback is intervention at the technical level to reduce waste. The further away from the technical level that feedback is provided, the more it is aimed at behavioural change. Scope is determined by the intended feedback target. Feedback should not be developed with multiple scopes in mind, as this will result in unnecessary additional information.

Step 3: Identify relevant temporal scale

Feedback must be temporally appropriate. For different levels of personnel and different levels of decision-making, feedback is required within different timespans of events occurring. This is shown in Figure 65. For process control, decisions must be made either in or close to real time. For every minute a process is run inefficiently, energy is wasted. As such, receiving feedback only at the end of the month will lead to unnecessary losses before the process can be improved. At higher levels, however, feedback may not be required as close to real time as the actions taken to correct them are related to planning and policies that cannot be implemented immediately.

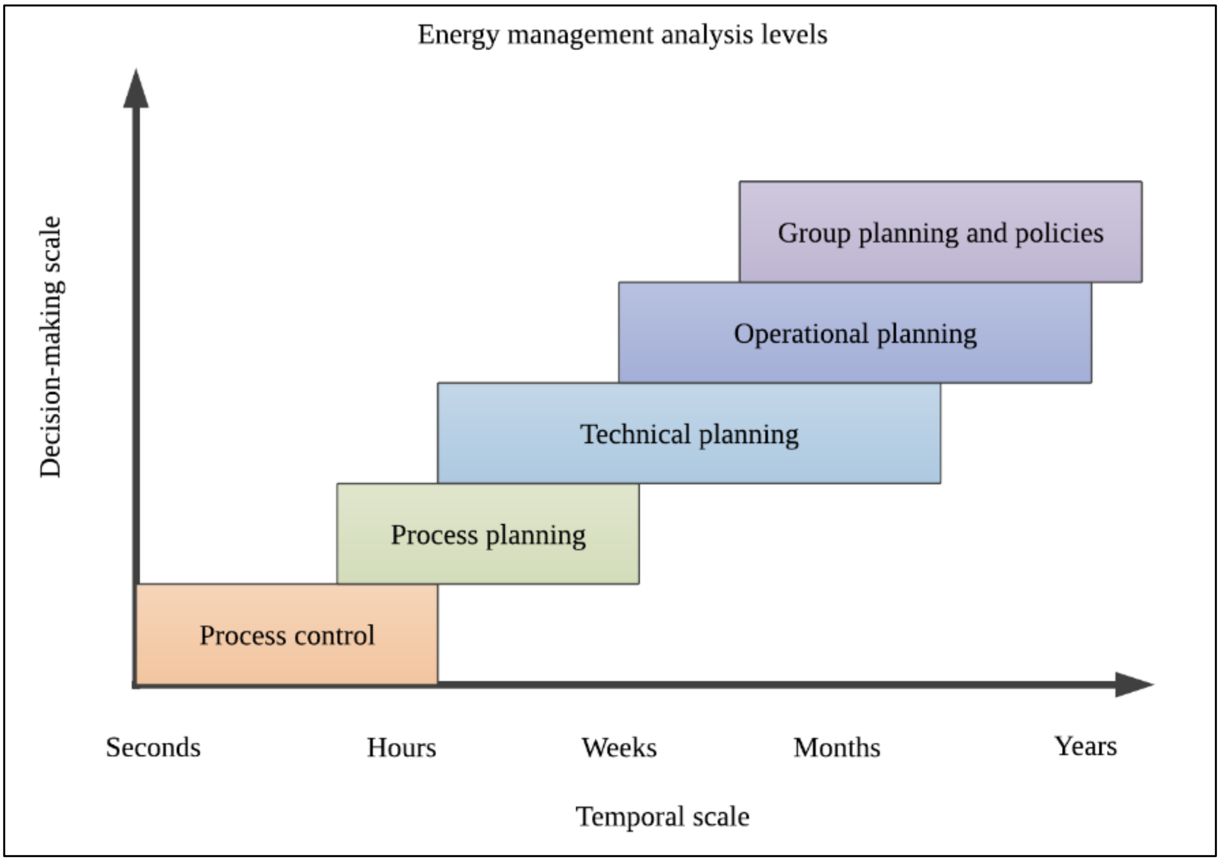

Figure 65: Scale of feedback levels at different appropriate temporal intervals

Step 4: Identify relevant frequency of feedback

Directly related to the timing of the feedback is the frequency and timespan covered by the feedback. At the process control level, feedback should be instantaneous, but does not need to cover a long time period – in many cases the feedback will only contain present performance and a trend. However, as feedback moves away from the technical level, feedback will be required less frequently, but must cover greater time periods. At top management level, feedback is typically only required at monthly or quarterly intervals. However, the feedback must include information for a far longer performance time period, which could be as much as several years.

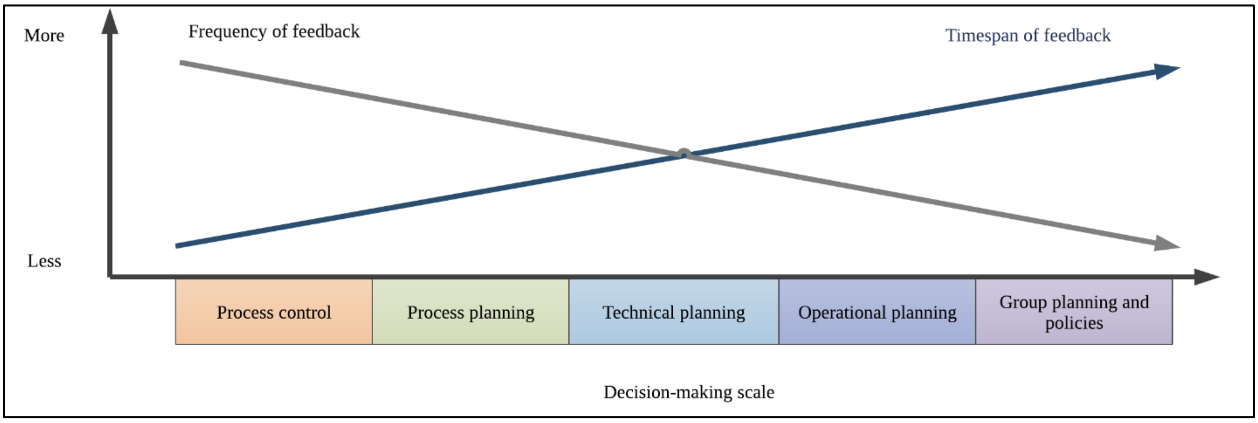

Figure 66: Frequency and timespan of feedback compared with decision-making level

Step 5: Identify appropriate level of analysis

Feedback must include a suitable level of analysis. This means that the data used to generate feedback must be analysed and condensed into information. The level of analysis must be suitable to achieve the desired results. When analysis is insufficient, it is often impossible to determine whether a problem exists. On the other end of the spectrum, where too much analysis has taken place, the feedback may point to a problem but not contain sufficient detail for corrective action to be taken. This is shown as a scale in Figure 67.

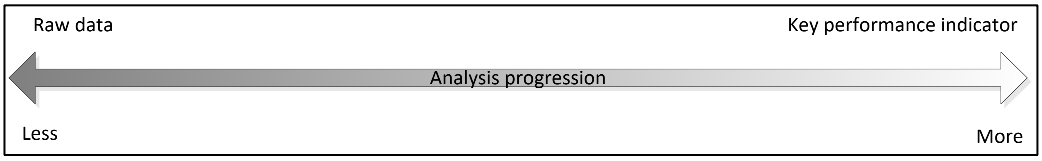

Figure 67: Spectrum of data analysis for feedback

Analysis should always be present in feedback. Where feedback is provided at the operational level, performance must be evaluated but not integrated. As such, each respective component that is underperforming will be identified individually. The expected performance must also be reported along with the factors in the performance equation that do not align.

At higher levels, analysis can be integrated to summarise performance only. However, at each level of feedback, the recipient should be able to identify the problem areas that lead to underperformance. Therefore, at departmental level, the individual systems in the department’s performance must be reported separately. This is shown in Figure 68.

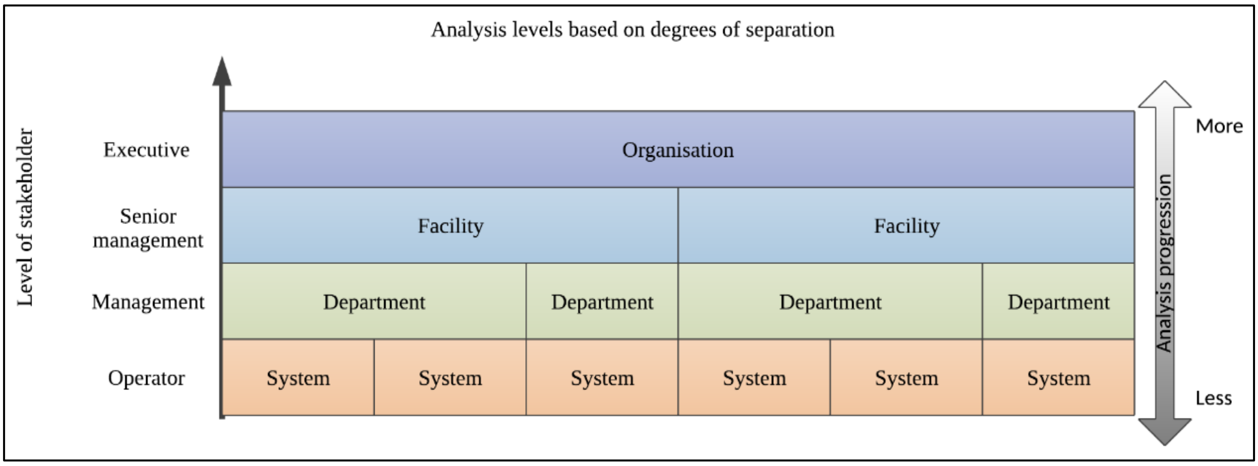

Figure 68: Analysis guideline based on levels of separation

All these factors can be combined as shown in Table 23. Once these factors have been considered and feedback has been developed, it can be implemented. Feedback can be developed for all stakeholders based on these guidelines. With feedback implemented, the operational energy management chain is completed and will effectively prompt action within the organisation.

Table 23: Feedback development criteria

	Operators	Management	Executive
Number of systems	Few (usually one)	Few	Many – usually integrated as business units or facilities
Information level	High – sufficient to diagnose problems	Moderate – sufficient to identify where problems are	Low – sufficient to know there is a problem
Purpose	Promote corrective action	Promote operational planning changes	Promote improved energy performance in organisation by showing whether policies and strategies are working
Type	Exception reporting, performance reporting	Exception reporting, performance reporting	Performance reporting, information
Temporal scale	Short time between event and feedback	Medium	Long
Frequency	Daily, whenever exceptions occur	Weekly	Quarterly
Analysis level	Moderate	High	Very high

3.6 Conclusion

In this chapter, a methodology was developed for implementing operational energy management in industry. The chapter started by discussing how systems are identified at facility level. Following this, the methodology for implementing effective measurement was developed. As part of this, a strategy for data management was presented. Following this, a systematic process for developing performance models for systems was presented. This process resulted in two different approaches based on what level of information was available at facility level. In the final section, a method for identifying feedback needs and implementing feedback was developed.

This chapter developed the various processes and methodologies required by the contributions of this study. The next step is evaluating the efficacy of the methodology and performing validation. In the next chapters, the application of this methodology will be validated through a case study in South African industry.

Chapter 4 Case study – Implementation

4.1 Preamble

To validate the methodology that was developed, it was applied in several industries in South Africa. The group at which the methodology was most extensively implemented is a South African gold mining group (GM Group 1). In this chapter, the implementation of the methodology on GM Group 1 will be shown. Results from the implementation will also be presented.

The mining group being considered is one of South Africa's three major mining groups. This group has six mining business units operating in the Witwatersrand Basin, both in Gauteng and the Free State. A seventh business unit operates an open-pit mine in the North West province. A summary of the group's operations is shown in Table 24.

Table 24: Summary of operations in GM Group 1

	Operation type	Depth	Contribution to group's total electricity consumption
Site 1	Two shafts	2.5 km	6.5%
Site 2	Single shaft	2.0 km	9.6%
Site 3	Two shafts	1.5 km	4.9%
Site 4	Surface shaft and sub-shaft	3.3 km	27.9%
Site 5	Single shaft	2.0 km	7.8%
Site 6	Two shafts	2.5 km	12.5%
Site 7	Single shaft	3.0 km	11.2%
Site 8	Single shaft	2.4 km	14.4%
Site 9	Single shaft	2.2 km	5.2%
Site 10	Open-pit mine	–	2.0%

The group's primary energy source is electricity purchased from the state utility, Eskom. Other minor energy sources include diesel and paraffin. This group also extensively uses compressed air and chilled water, which are developed on-site and sent underground. In South Africa, energy makes up 16% of the group's operating costs.

GM Group 1 had previously implemented several Eskom-funded DSM projects on various operations. These energy and energy cost saving projects were identified and implemented by various South African ESCos. These projects were effective at providing savings. However, by using external experts and funding, the emphasis of incorporating energy management into the corporate structure was delayed.

As a result, the existing processes and infrastructure to support energy management were limited. Energy sub-metering was rolled out throughout the group from 2012 onward. However, some of the metering still required verification. It was also uncertain whether the metering scope had been sufficient.

Monthly energy budgets were determined annually, based on a historical figure that was adjusted for increases or decreases in production. Beyond mandatory reporting, only a single energy report was in place. This report consisted of monthly feedback showing the energy consumption of each site. These reports were found to be unclear, which made it difficult to identify which areas required specific attention.

The energy management team consisted of an energy manager and several electricians to support him. Overall, it was found that there was little capacity for additional energy management work to be done. A significant portion of the energy manager’s time was used to ensure that energy projects were implement smoothly. One of the electricians was tasked with manually compiling the monthly energy feedback reports.

Operational energy management was implemented within this group prior to the implementation of a formal ISO 50001-compliant energy management system.

4.2 Overview of implementation

The implementation of an operational energy management system throughout the group consisted of three phases. Firstly, the accuracy and scope of existing metering had to be verified to ensure it was sufficient for the intended purpose. This also included identifying areas where additional metering should be considered by the group. Secondly, the new budgeting methodology had to be implemented to provide accurate budgets up to half-hourly level. Finally, various levels of feedback had to be identified, and the relevant feedback structure put in place.

4.3 Measurement and data management

4.3.1 Existing infrastructure

In South Africa, GM Group 1 primarily uses electricity to fulfil energy needs. Although some combustible fuels are used in company vehicles, this is small enough that it is not reported in the group’s annual report. As such, electricity will be the primary focus of this section.

The mine group is subdivided into several business units. Each business unit has its own Eskom account, with multiple points of delivery. As the electricity consumption for the different points of delivery is shown on the Eskom accounts, it is possible to determine verified electricity consumption of the different operations from these invoices. This is shown in Figure 69.

The mining group had already installed sub-metering on-site prior to the beginning of the case study. However, verification of the meters was outstanding. Further, data was centralised to a server, but processes were not in place to ensure the veracity of the data.

4.3.2 Verification of existing metering

To verify the data, the check metering was compared with the Eskom accounts of the different operations for a one-year period. The results are shown in Figure 69. In the figure, the monthly average electricity consumption measured by the utility and the check meters is shown. The maximum and minimum deviation from the utility meter is shown as an error bar.

From Figure 69, it is clear that most check meters were accurate. The absolute error on the group’s total electricity consumption was 2.06%. Site 4 and Site 9 were identified as needing further attention. For Site 10, data from the check meter was not available, and the data from the remaining meters showed that there was not sufficient metering on-site. However, as Site 10 contributes only 2% of the total group electricity consumption, this was identified for attention at a later point only. It was agreed with the mine that attention would not be given to Site 10 for the remainder of the implementation.

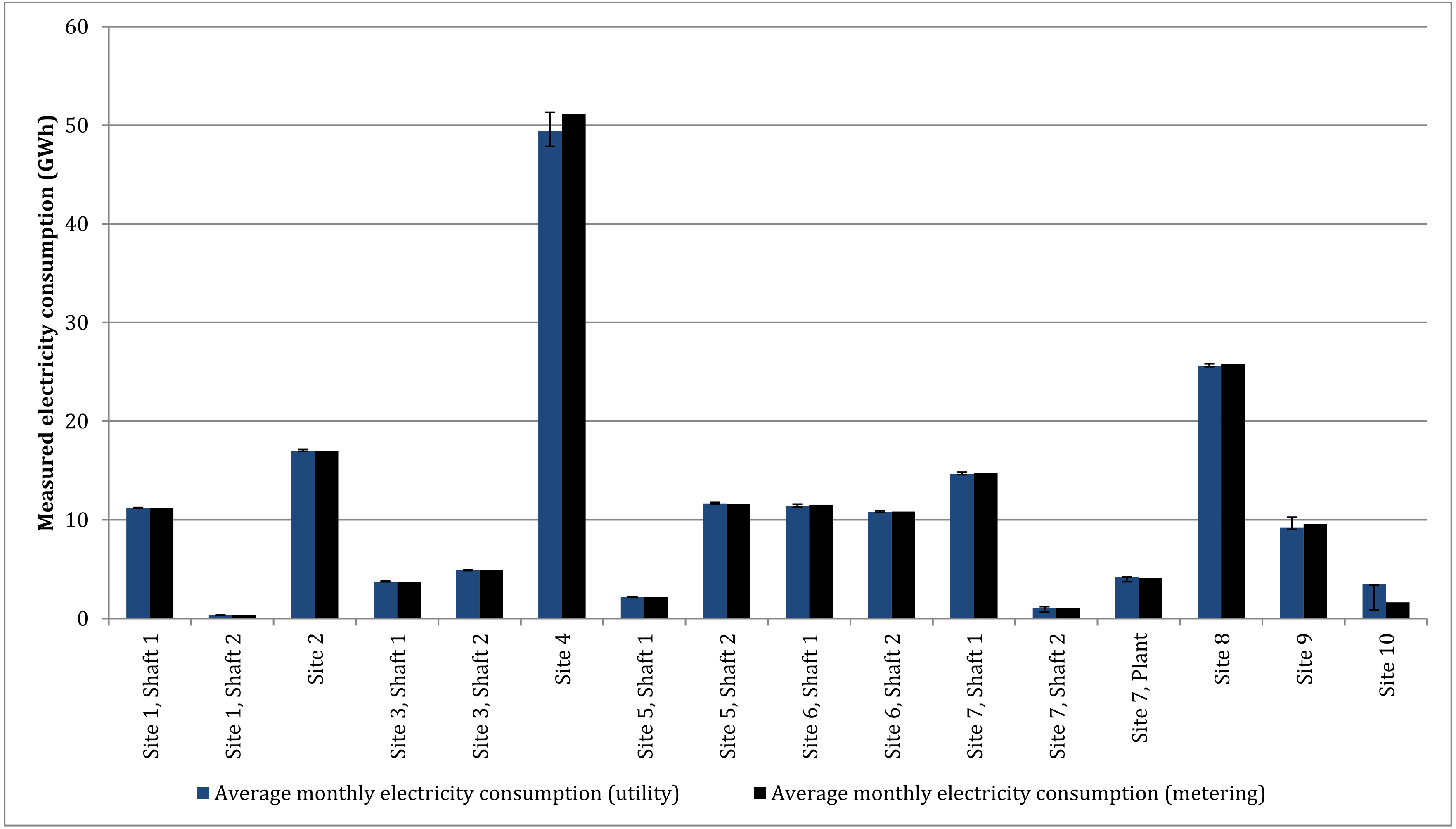

Figure 69: Electricity consumption by check metering and utility

The next step is identifying the electricity-consuming systems present at each operation, and identifying the energy consumption of the different equipment. This can be done either from literature, or from the inventory of electric motors on the different operations.

Literature shows a distribution of electricity consumption on gold mines as shown in Figure 70. This distribution provides a starting point from which approximate energy consumptions can be estimated for the different systems in the mining group.

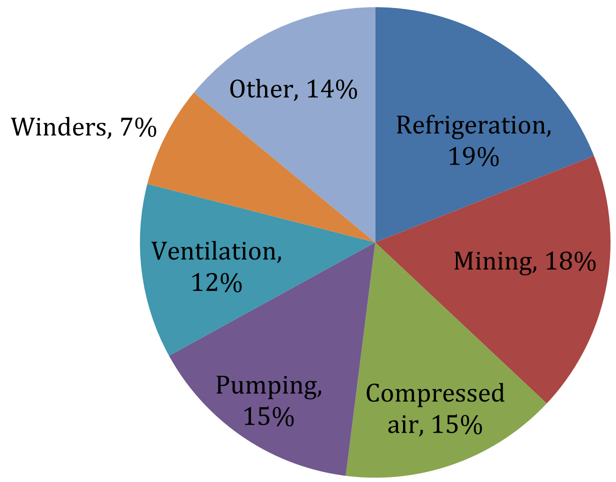

Figure 70: Typical gold mine electricity consumption distribution [98]

Additional data available from the mine was the number and installed capacity of electric motors and other components on the mine. This data also included mine estimates for the number of days per month and hours per day each component was expected to operate on average. Using this data, it was possible to develop an estimate for the electricity consumption of each system.

Table 25 shows a breakdown of the operation of Site 1 of GM Group 1. The operation is split into shafts and shaft systems. Finally, two estimates are provided based on literature and the data available from the mine. The different systems are prioritised according to information supplied by the mine, as shown in Table 25. On Shaft 1, the compressor system is the largest electricity consumer, and is marked as (1). The only exception to this categorisation is (5), which consists of three smaller support systems, which had been grouped together during the metering process.

Table 25: Breakdown of Site 1's estimated annual electricity consumption by system

Operation	Shaft/plant	System	Estimated consumption based on literature	Estimated consumption based on installed capacity and operational information	
Site 1	Shaft 1	Mining	24.22 GWh	13.39 GWh	(6)
		Pumping	20.18 GWh	15.62 GWh	(4)
		Fans	16.15 GWh	17.38 GWh	(3)
		Hoisting	9.42 GWh	11.90 GWh	(7)
		Compressors	20.18 GWh	37.56 GWh	(1)
		Refrigeration	25.57 GWh	22.63 GWh	(2)
		Hostel	18.84 GWh	14.18 GWh	(5)
		Surface			
		Filtration			
	Shaft 2	Hoisting	0.51 GWh	5.43 GWh	
		Mining	1.31 GWh	1.06 GWh	
		Pumping	1.09 GWh		
		Surface	1.02 GWh	0.24 GWh	
		Backfill		1.07 GWh	

Had sub-metering not already been incorporated, this prioritisation would have been used to identify which systems should be metered first. However, as sub-metering was already in place, this recommendation could be checked against actual data. The actual energy consumption of the different systems for 2014 is shown in Figure 71. As the figure shows, the available information predicted the order of energy consumption of the systems with reasonable accuracy, with only one system that would have been given higher priority than what is appropriate.

The system level metering was compared with the site incomer check meter. The data used was half-hourly for a period of one year. This was done, firstly, to show that most energy carriers had been metered, and, secondly, to verify the accuracy of the check meters. It was shown that for Site 1, Shaft 1, the sub-meters reflected 97.8% of the check meter's values. The correlation between these two meters was 98.5%. Thus, all SEUs were measured accurately. This is shown visually in Figure 72. In this figure, the data for one week is shown, with the main incomer meter shown in black. The different sub-systems are shown as a stacked area chart. As can be seen, the stacked chart closely follows the main incomer check meter.

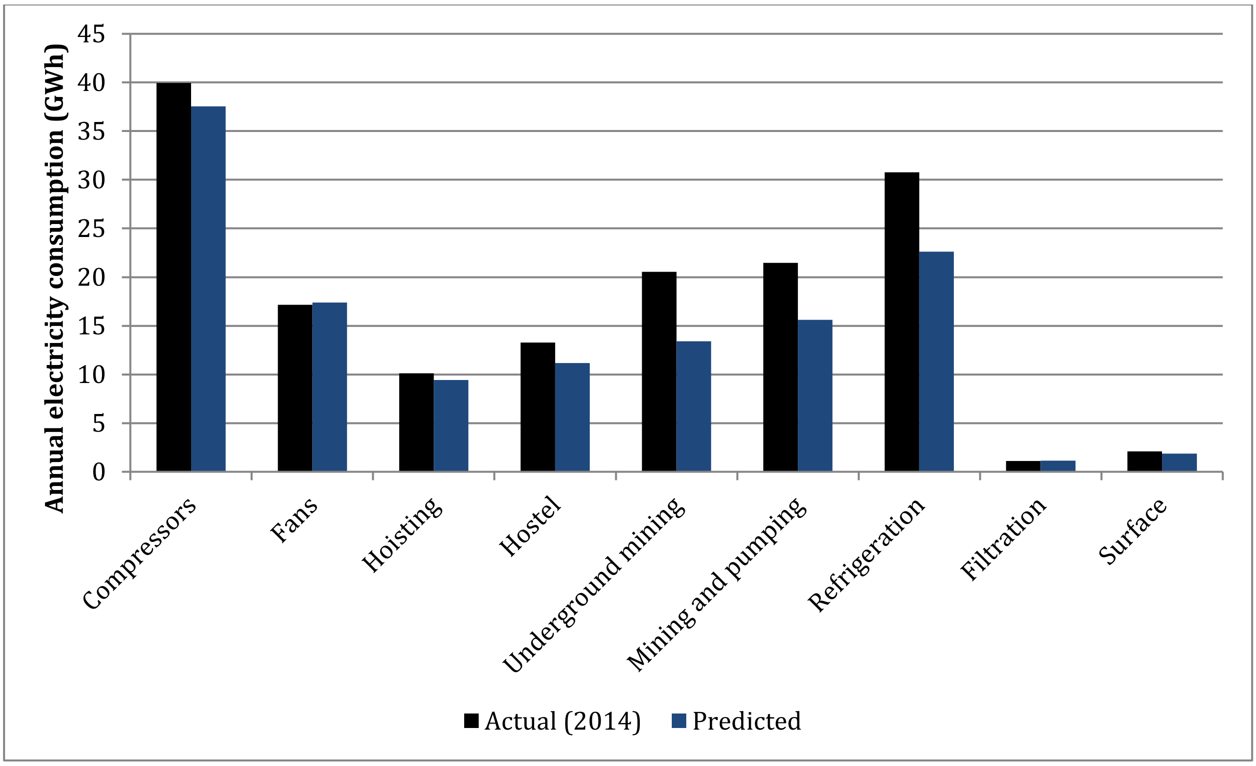

Figure 71: GM Group 1, Site 1, Shaft 1 annual electricity consumption breakdown by system

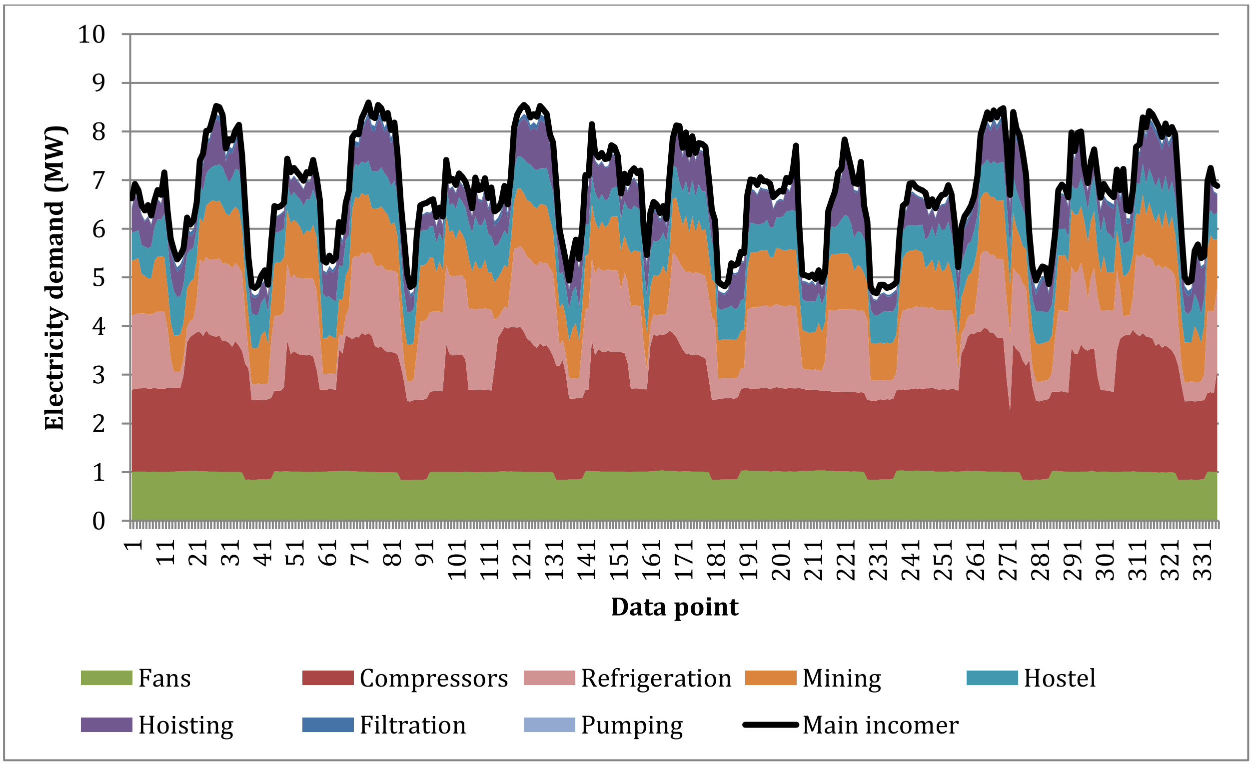

Figure 72: Electricity demand for Site 1, Shaft 1 sub-systems and main incomer check meter

The results from the remainder of the sites will be discussed next. Table 26 shows the results from analysing the sub-metering throughout the group and comparing the data with the verified check meter data. For a one-year period, half-hourly data from the sites was used to determine the accuracy of the sub-metering, as well as whether significant systems had not been metered.

Table 26: Results from sub-metering verification

Site	Shaft	Sub-metering error	Standard deviation	Sub-meter correlation	Data availability
Site 1	Shaft 1	2.2%	2.4%	98.5%	97.1%
Site 2	Shaft	1.2%	33.8%	54.9%	99.6%
Site 3	Shaft 1				
	Shaft 2	1.9%	3.6%	99.0%	100.0%
Site 4[12]	Shaft	0.4%	4.9%	84.0%	39.8%
Site 5	Shaft 1				
	Shaft 2	0.5%	1.6%	99.0%	≈100.0%
Site 6	Shaft 1	0.5%	3.9%	98.2%	98.0%
	Shaft 2	8.4%	9.2%	89.8%	100.0%
Site 7	Shaft 1	1.0%	1.7%	98.4%	99.9%
Site 8	Shaft	1.9%	3.3%	97.6%	99.7%
Site 9	Shaft	3.4%	5.6%	83.0%	99.3%

The four categories used to analyse the data were sub-metering error, standard deviation, sub-meter correlation and data availability. The sub-metering error columns shows the average absolute difference per measurement interval between the check meter and the total of the system sub-meters. In most cases, the total of the sub-meters was lower than the check meter because of losses or unmetered energy users.

The next column shows the standard deviation of the sub-metering error data set. This is indicative of the magnitude of change in the sub-metering error field. A small value here indicates that the sub-meter remains within a narrow margin of the check meter. A large value indicates that there are instances where the total of the sub-metering varies greatly from the check meter.

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[12] Due to the large number of data points with data loss on Site 4, a two-year period was evaluated.

The sub-meter correlation column shows the correlation between the check meter and the total of the sub-meters. A high standard deviation value, along with a poor correlation, is indicative of a system that is unmetered and is causing fluctuations in electricity demand.

The data availability column shows the number of complete data points that were available in the data set. A data point was judged as complete when there was data available for both the check meter and all the sub-systems. Low data availability is indicative of communication problems between the meters and the data centralisation system, which will be discussed further in the next section. However, as large gaps in available data would affect the accuracy of the prediction, it is listed here.

Values shown in green indicate a margin of error that is small enough to be acceptable. Values shown in yellow are indicative of requiring further investigation by mine personnel. Values shown in red are unacceptable for use as part of an operational energy management strategy, and would need to be corrected before being used further.

For all shafts at Site 3, Site 5, Site 7 and Site 8, the sub-metering was determined to be accurate enough to be indicative of real electricity demand. For Site 6, Shaft 1, this was also the case. Site 1 showed a medium sub-metering error and data loss. The sub-metering error could be indicative of a small, unmetered baseload being present in the system. Upon further investigation, it was found that the measurement device for the fans sub-system went offline after the mine had shut down for Christmas holidays in 2014; for the remainder of the year data availability had been 99.9%. Site 6, Shaft 2 and Site 9's sub-metering deviated from the check meters significantly enough that they were identified for further investigation by mine personnel.

For Site 2, there was a significant deviation between the sub-metered electricity consumption and the check meters. Figure 73 shows the profiles of the sub-metering that was available on the shaft for a period of several days in January 2014. The solid black line shows the profile of the check meter on the main incomer to the facility. The stacked area charts show the various metered sub-systems. As is shown in the difference between the solid black line and the coloured areas on the graph, there appears to be an unmetered and highly variable load in the system.

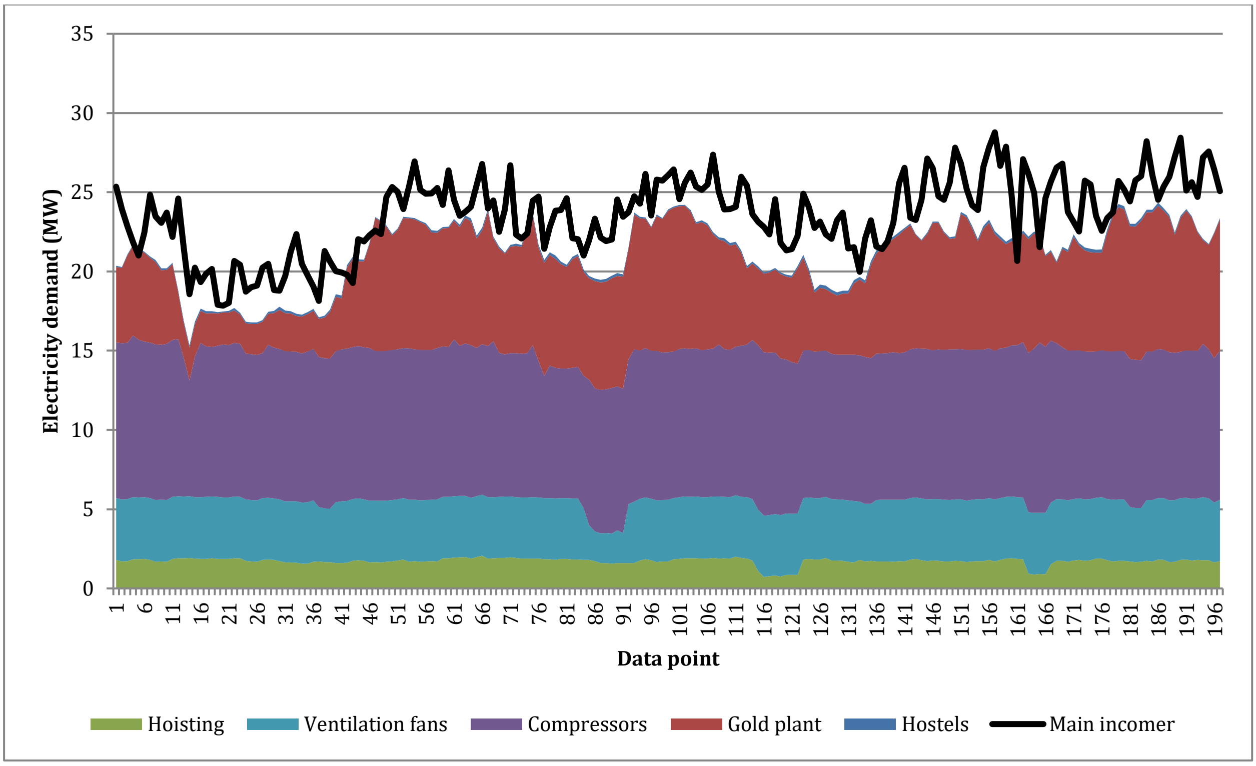


Figure 73: Site 4 electric power profile of sub-meters and check meter on main incomer

Further investigation also showed a highly irregular profile for the hoisting sub-system. The installed capacity and expected load factor of the hoisting system on Site 2 are shown in Table 27. It was concluded that the profile associated with the hoisting system was unlikely to be correct. It was possible that the meter had been installed at the incorrect location, or had been improperly identified. The issue was identified for further investigation on-site.

Table 27: Installed capacity and expected load factor of hoisting system on Site 2

Winder	Motor kW	Expected load factor	Average demand (kW)
Man winder	3 400	11%	374
Man and material winder	3 400	19%	646
Material winder 1	5 965	9%	536
Material winder 2	1 350	0%	0

As shown by Table 26, it was found that the data availability for Site 4 was the worst in the group. Site 4 had only 39.8% data availability, meaning that sub-meters reported data for less than 40% of the time. Although the other indicators were within acceptable limits, the fact that such a large quantity of data is not available makes the reliability of the indicators questionable.

The sub-systems with the highest number of faults in data measurement were identified for attention. Figure 74 shows a breakdown of sub-system data loss for Site 4, ordered per number of data loss occurrences for the sub-systems. As the graph shows, five sub-systems were responsible for more than 75% of the data loss experienced at the site.

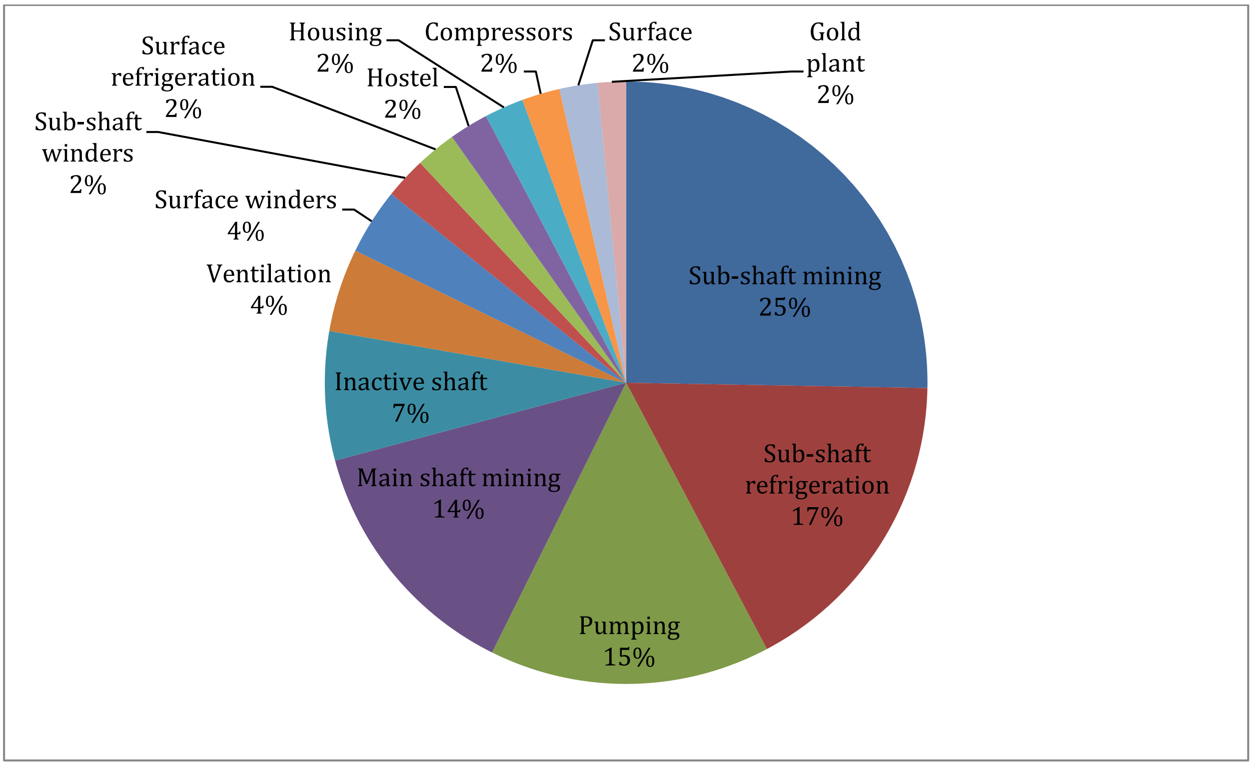


Figure 74: Data loss by sub-system for Site 4

To prioritise the investigation and correction of data communication on Site 4, the average daily electricity consumption of each sub-system was multiplied with the total number of days for which data was lost. The resulting number provides and estimated quantity of electricity consumed by the system for which no data was available. Table 28 shows the results.

An important result from Table 28 is that despite having fewer instances of data loss, the data for the gold plant was given a high priority because of the high daily electricity consumption of the plant. The shaded area of Table 28 accounts for 82% of the quantity of electrical energy data lost. The rand value of this electricity is R85 million. For most commercial companies, having such a large expenditure of which the cause could not be determined would not be acceptable. This section of Table 28 should therefore be addressed as soon as possible.

Table 28: Priority list for Site 4's sub-metering

Priority	Sub-system	Days with data loss	Average daily electricity consumption (kWh)	Data loss quantity (kWh)
1	Sub-shaft mining	384	235 850	90 566 712
2	Pumping	229	210 346	48 169 351
3	Main shaft mining	205	199 515	40 900 628
4	Sub-shaft refrigeration	258	124 858	32 213 449
5	Gold plant	23	1 388 968	31 946 261
6	Ventilation	68	191 630	13 030 867
7	Compressors	31	293 225	9 089 992
8	Inactive shaft	105	78 125	8 203 200
9	Housing	32	193 933	6 205 873
10	Hostel	32	170 542	5 457 361
11	Surface winders	54	75 999	4 103 956
12	Surface refrigeration	33	117 616	3 881 338
13	Sub-shaft winders	34	22 992	781 752
14	Surface	31	14 791	458 535

Further, there were several sites where two large electricity-consuming systems were combined, specifically mining and pumping. This was done primarily because it was cheaper, as both underground systems were typically fed with a single supply from surface. Underground pumping systems are a good target system for operational energy management because they are often controlled from a single control room, and consist of a small number of large energy consumers (5–15 pumps) rather than a large number of small energy consumers. Combining the pumping system with the underground mining system means that there is reduced clarity on the performance of the pumping system.

Another issue identified was a lack of sub-metering on gold plant sub-systems. While most gold plants were measured as a total system, very few had metering on the different large energy-consuming sub-systems, such as the milling circuit. As previous research identified the gold plant milling circuit as a potential target for time-of-use (TOU) optimisation [99], there may be potential savings that are not being achieved.

By estimating the cost of electricity supplied to each of the systems, as well as the remaining lifetime of the mine, the potential need for further metering was identified and communicated to the mine. This is shown in Table 29, where the unmetered systems are listed.

Table 29: Annual electricity consumption and cost for unmetered systems

Site	System	Annual electricity consumption (kWh)	Annual electricity cost (R)
Site 2	Milling	46 688 400	R32 681 880
Site 7	Milling	36 541 715	R25 579 201
Site 4	Milling	25 300 712	R17 710 498
Site 2	Treatment	21 526 680	R15 068 676
Site 3	Milling	13 941 006	R9 758 704
Site 4	Treatment	13 327 410	R9 329 187
Site 7	Treatment	10 591 802	R7 414 261
Site 7	Elution	5 825 491	R4 077 844
Site 4	Compressed air	5 652 706	R3 956 894
Site 2	Compressed air	5 286 326	R3 700 428
Site 1	Mining	4 907 637	R3 435 346
Site 1	Pumping	4 421 781	R3 095 247
Site 3	Pumping	4 069 561	R2 848 693
Site 4	Elution	3 883 748	R2 718 624
Site 3	Thickening	3 825 200	R2 677 640
Site 3	Absorption	3 664 993	R2 565 495
Site 4	Backfilling	2 041 141	R1 428 798
Site 3	Mining	754 698	R528 289
Site 3	Surface	438 000	R306 600

The expected electricity consumption of each system has been combined with available data for the site and the other systems to develop a more accurate estimate of annual electricity consumption. This annual consumption was multiplied by the average cost of electricity for the group to determine the actual cost for unmetered electricity. Based on this figure, as well as the results achieved in this case study with other similar systems, the estimated savings obtainable were determined. This was compared with the cost of installing additional meters and the expected lifetime of the mine to determine whether additional metering could be motivated for operational energy management.

Following this, the available meters for most sites were verified as reasonably accurate. Metering problems were identified and could be communicated to the mine. However, the issue of data management still had to be addressed. This will be discussed next.

4.3.3 Data management and verification

This section will first present an overview of the existing infrastructure that was in place. Following this, the common problems that occurred regarding data management will be discussed. Finally, the systems and preventative measures that were put in place will be discussed.

GM Group 1’s infrastructure is highly distributed. With operations in seven regions and three provinces, communication networks are not always reliable. Even on individual shafts, large electricity-consuming systems are often located far apart. The mine had implemented a data centralisation system along with the sub-metering project that had been completed in 2013. This resulted in electricity measurement data being available in a central location. However, it was found that several problems hampered this system, as will be discussed further in the following paragraphs.

Figure 75 shows a highly simplified diagram of the sub-metering data communication network of GM Group 1. On most shafts, smart measurement devices were connected on a communication network to a global system for mobile communications (GSM) modem device. Data would be sent once every 24 hours via the GSM modem. The data sent would be for the entire preceding 24-hour period. Each site had several meters for each large sub-system, which communicated either through shared or dedicated GSM modems.

The only exception to this was Site 4, which had a dedicated on-site server. This server was linked via a local area network to the measuring devices. The server continually read data from the measuring devices, aggregated it, and stored the data locally in a database. The data was also sent via a GSM modem once every 24 hours.

All data was sent to a centralised data server. On this server, data was aggregated and stored in half-hourly intervals. Historical data was also stored on the server from the inception of the meters. There were several modes through which the data could be accessed. The simplest form, which was primarily used by the mine personnel, was to log into the system via a web portal through which mine personnel could view trends of the stored data.

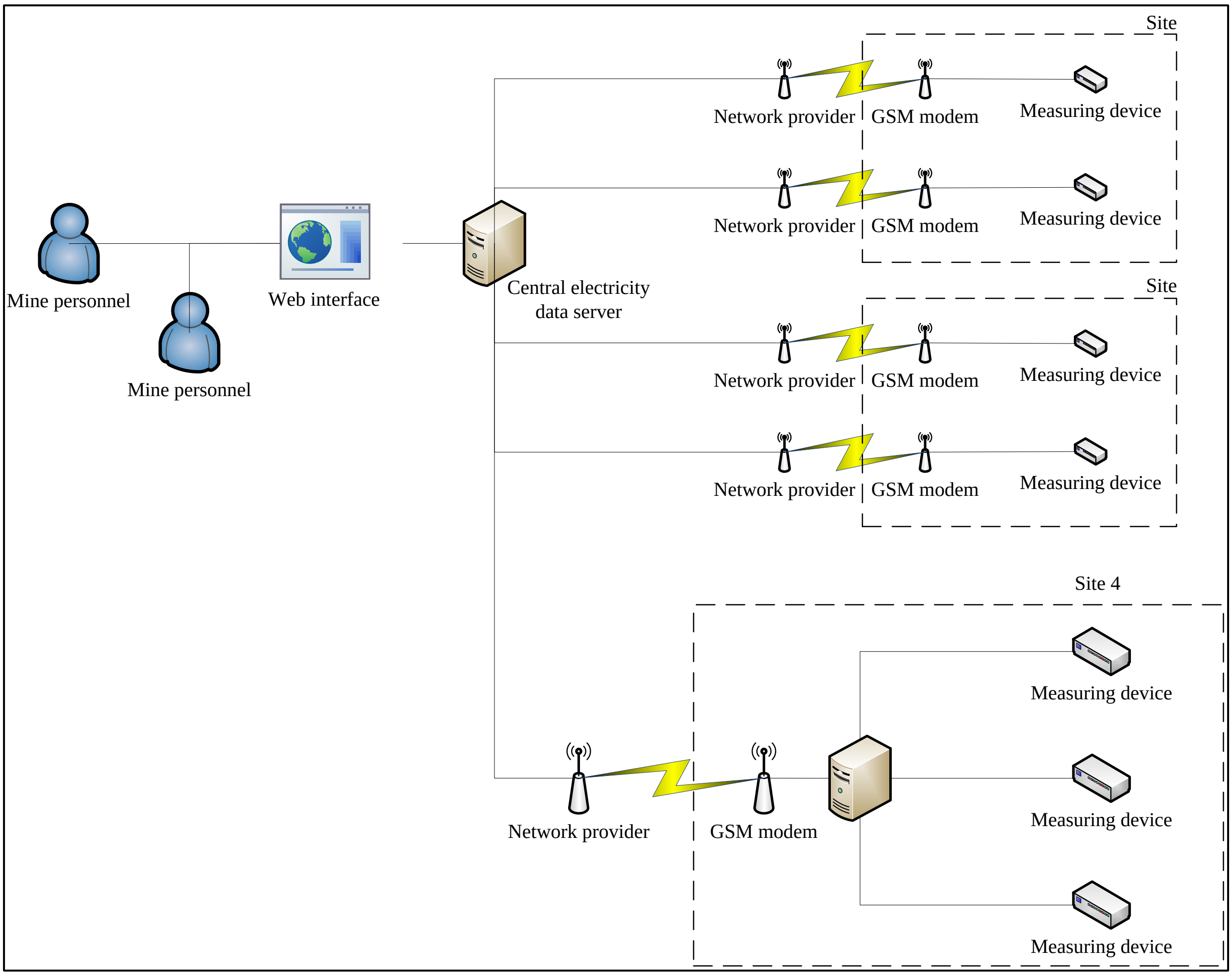


Figure 75: Layout of sub-metering data communication network for GM Group 1

There were several problems with the existing implementation. First, the system only captured electricity measurement data. Without the ability to capture any information about energy drivers, the system lacked the ability to effectively report on energy performance. However, the system did provide the ability to compare the actual consumption with a budget figure. Prior to the implementation of this methodology, however, these budgets were largely ineffective, as will be discussed in the next section.

The second problem with the existing system was due to a lack of accessibility of the system. Although most of the high-level personnel had access to the system, only two of the mine's personnel reported using it. There are several factors that contributed to this, including the difficulty of operating the system, the complexity of setting up and receiving feedback from the system, and that most of the mine's personnel had other more pressing matters to attend to.

Further, mine personnel with the most immediate ability to impact energy performance, namely operators, did not have access to the system. As such, energy management activities resulting from this system would not allow operators to participate, or receive feedback when pertinent.

The third problem associated with the existing set-up was that it was focused towards capturing and reporting aggregated data. Although this data is useful for longer term planning, the lack of short term feedback meant that problems would typically go unattended for several days or weeks without being addressed.

There were also several problems with data reliability over the implementation period. The most common problem was a loss of communication with the site. This occurred typically when the GSM modems failed. Other causes of communication failure included poor signal reception to remote modems (such as caused by bad weather). In this case, the actual data measurements would not be present in the data table. However, budget data was still available. Prior to the implementation of a data management and verification strategy, this would result in budgets that were counted against consumption that had not been reported. The overall result of this would be that the budget would far exceed consumption for the period.

Another common occurrence was due to the inherent quality of the meters. Most meters were totalising devices, meaning that they held a cumulative count of electricity consumed since installation. However, these devices had a maximum number of digits they could fill before reverting to zero. For example, a device storing eight characters would be able to store a maximum value of 99 999 999. In many cases, when the device reverted to reading 00 000 000, a large positive or negative spike would occur in the data.

This is shown visually in Figure 76A. In the example, the meter for the compressor system ticked over between 15:00 and 15:30. This resulted in a half-hourly demand figure of nearly 3 GW. As reference, Eskom has approximately 47 GW of generation capacity. If this demand had occurred, it would have resulted in catastrophic damage to the mine’s electricity supply infrastructure. As such, it is safe to conclude that the reported data is not correct. When this occurs, there are two potential options. The first is to ignore the data point and its corresponding budget. Alternatively, as the data point is small compared with the rest of the day, its data can be interpolated or replaced by another measurement where available. In Figure 76B, the red line shows the data point as interpolated from the data preceding and succeeding the point.

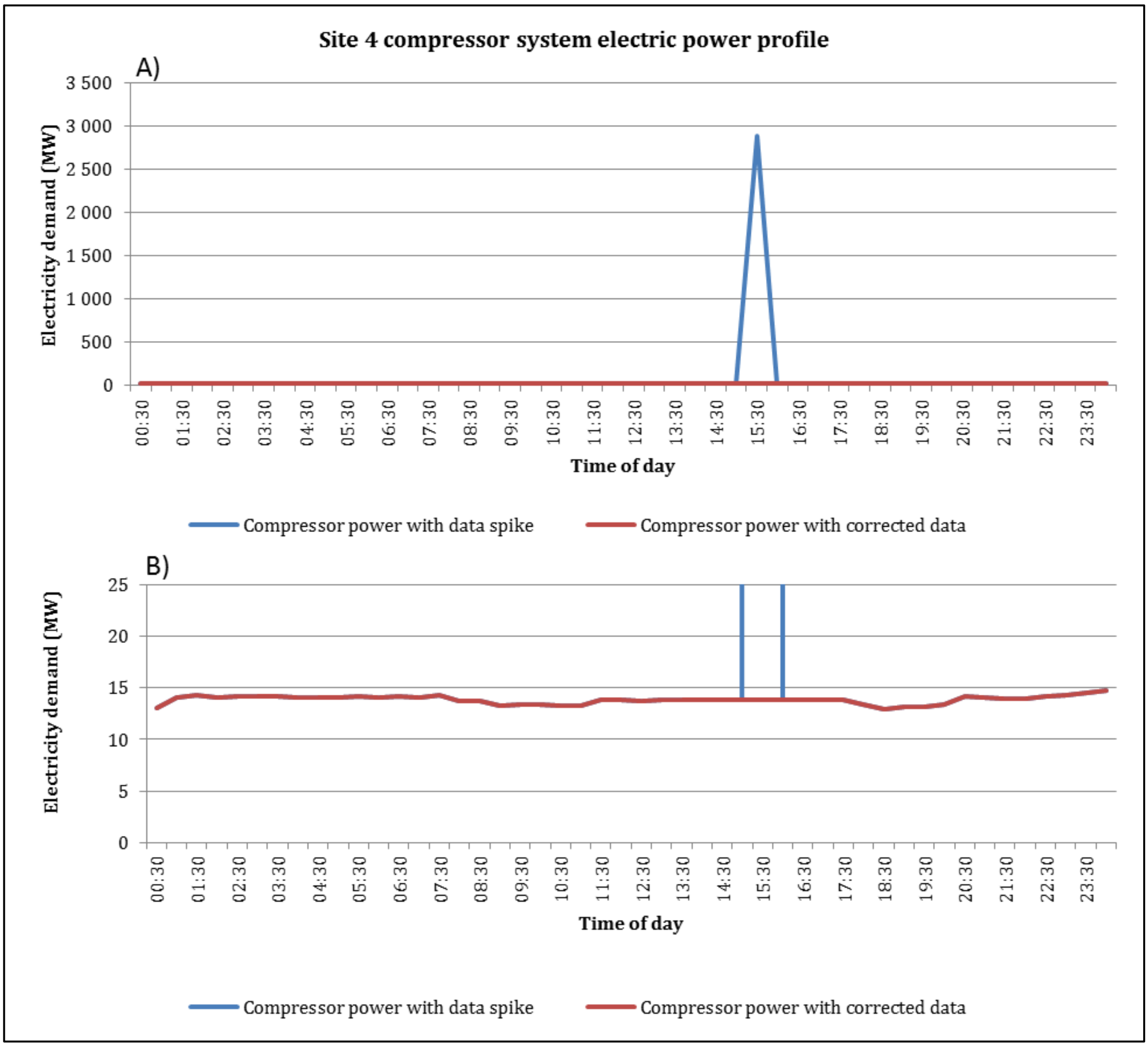


Figure 76: Site 4 compressor system electric power profile for 31 May 2016

Another common problem occurred when the measurement devices themselves stopped working or communicating. In these cases, it was common for the database to be populated with numeric zero entries. As a result, the system would report that data was present, even though the data was incorrect. This made it necessary to include logic in the data management system to prevent this from occurring.

There was no process for handling these types of problem within the system. Identifying problems was entirely dependent on whether mine personnel noticed them while working with the data. This means that only reactive action could be taken if a problem was identified. To prevent this type of problem from occurring, a process for data management was developed. This was implemented by a system that checked data as it was being incorporated into the new reporting system.

A layout of the system that was implemented is shown in Figure 77. This new server operated a system capable of integrating all data sources relevant to operational energy management. This included electricity and budget data, but also energy drivers such as production, maintenance and planning data. The server also had an integrated data verification service. With this service, unreliable data could be actively identified.

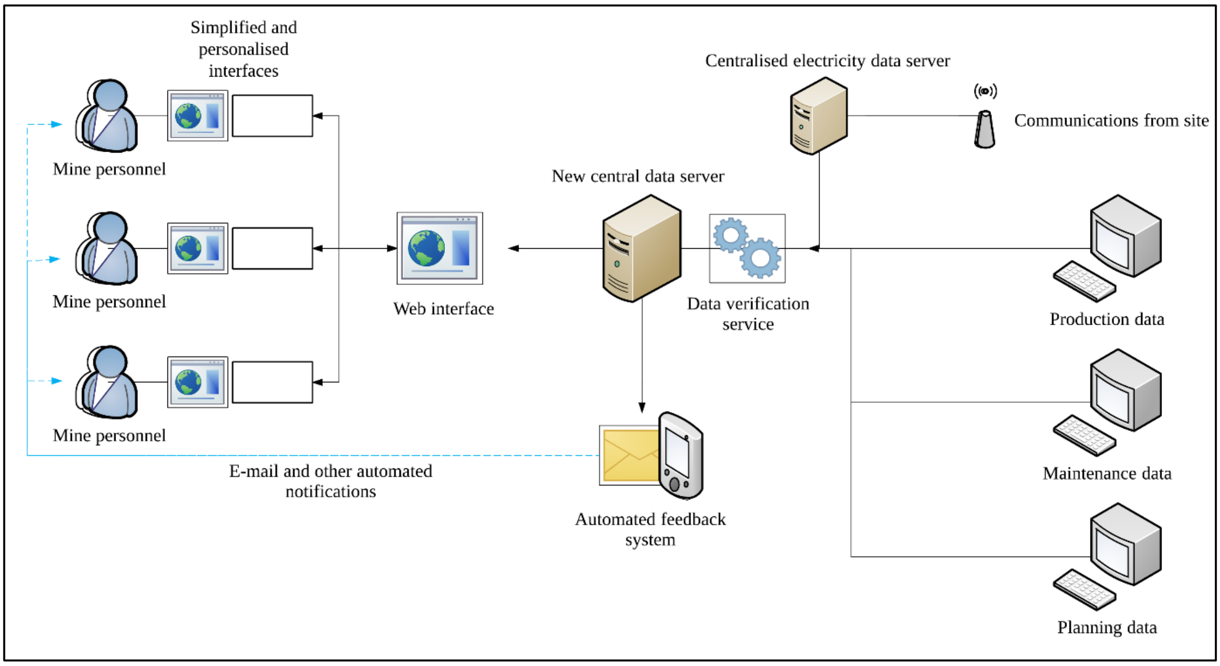


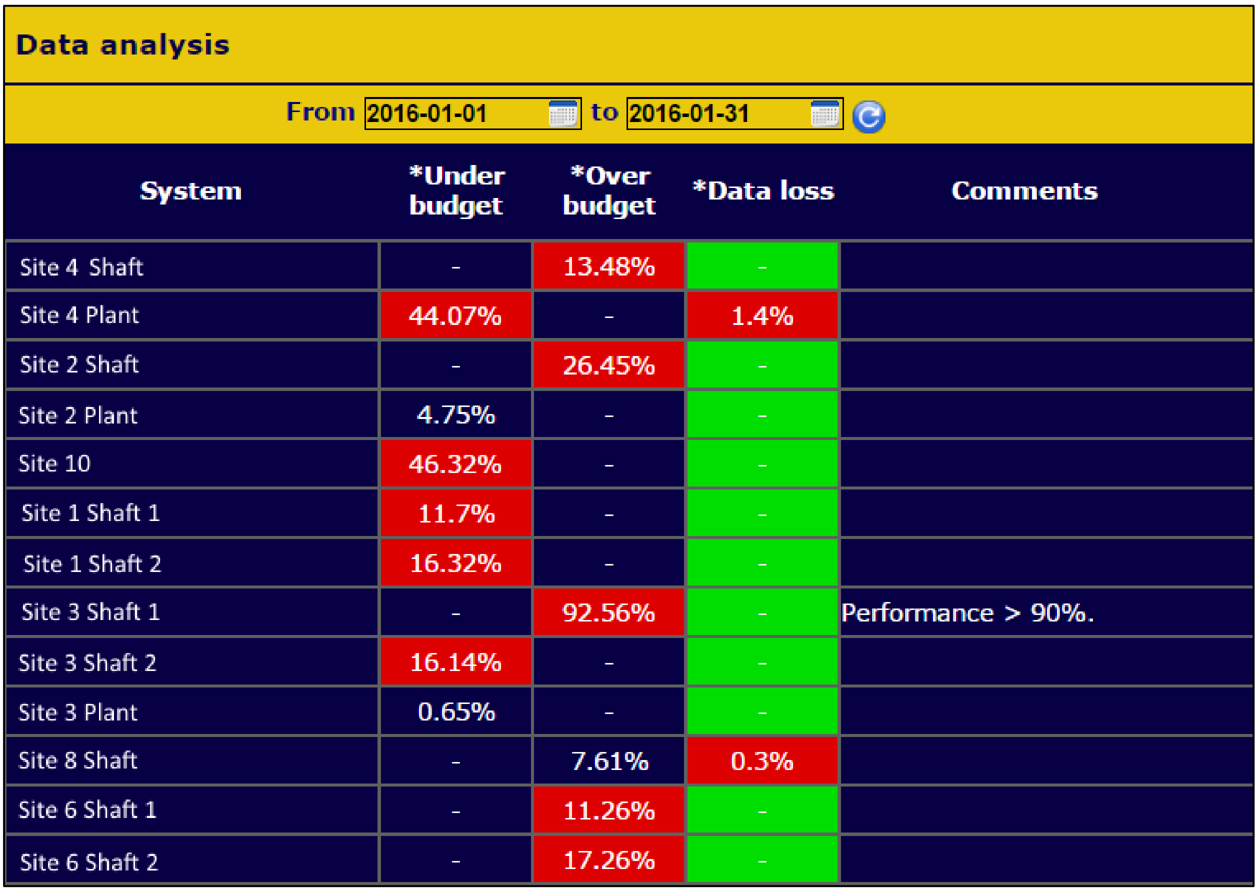
Figure 77: Layout of data centralisation and management system implemented for GM Group 1

The system also included a web interface. However, this interface was developed with the needs of the various users in mind. Personalised home screens were developed for mine personnel as they did not require detailed knowledge of the working system. Personnel were also not required to set the system up in anyway after logging in.

However, as most mine personnel would still be too busy to access the system unless they were looking for specific information, the system also included an automated feedback system. This system included automated feedback generation and distribution capability. Feedback reports for mine personnel could be triggered and distributed to the various mine personnel at predetermined intervals and when exceptions were detected.

To prevent incorrect reporting due to these data and communication errors, algorithms were put in place to detect when errors had occurred. These algorithms assisted in identifying situations where data was unreliable. By managing the incorrect data effectively, errors that would result because of them could be avoided.

Figure 78 shows a visual analysis of the data loss for the group. Sites where no data loss occurred are shown in green. Data loss is shown in red, with a percentage of the data that is not available. Using this information, the veracity of the electricity data for the shaft can be determined.



Data analysis

From 2016-01-01 to 2016-01-31

System	*Under budget	*Over budget	*Data loss	Comments
Site 4 Shaft	-	13.48%	-	
Site 4 Plant	44.07%	-	1.4%	
Site 2 Shaft	-	26.45%	-	
Site 2 Plant	4.75%	-	-	
Site 10	46.32%	-	-	
Site 1 Shaft 1	11.7%	-	-	
Site 1 Shaft 2	16.32%	-	-	
Site 3 Shaft 1	-	92.56%	-	Performance > 90%.
Site 3 Shaft 2	16.14%	-	-	
Site 3 Plant	0.65%	-	-	
Site 8 Shaft	-	7.61%	0.3%	
Site 6 Shaft 1	-	11.26%	-	
Site 6 Shaft 2	-	17.26%	-	

Figure 78: Visual representation of data loss analysis

This data management process and system allowed data to be managed proactively. By including automated preventative measures to avoid using corrupted or lost data, the accuracy of reporting was increased. In addition, the data monitoring system allowed users to continually track metering problems.

Following this, reliable data was available for analysis. In the next section, the usage of the data to develop targets for the mine group will be discussed.

4.4 Data analysis

4.4.1 Existing budget methodology

To quickly incorporate data analysis into existing processes, it was decided to use the mine's energy budgeting process. The mine group uses electricity budgets, which are calculated prior to the beginning of each financial year based on the installed capacity of electric motors on each mining operation. The budgets are monthly total electricity consumed budgets (kWh), and are multiplied by an average cost (cent per kWh) to determine the financial budget.

The existing budgets were found to be largely ineffective in supporting operational energy management, primarily due to their inaccuracy. To implement operational energy management, a highly refined budgeting methodology would need to be implemented.

There were several problems with the existing methodology used by the mine. Firstly, the existing methodology was found to be substantially inaccurate. Figure 79 shows the monthly budgeted and actual electricity consumption for Site 1, Shaft 1 for a three-year period. As the graph shows, the budgeted electricity consumption exceeded the actual consumption each month. The average difference between the budget and actual consumption was 12%. The budget was only within 5% of the actual energy consumption for four months throughout the entire period. Thus, the existing methodology was highly inaccurate in developing a budget.

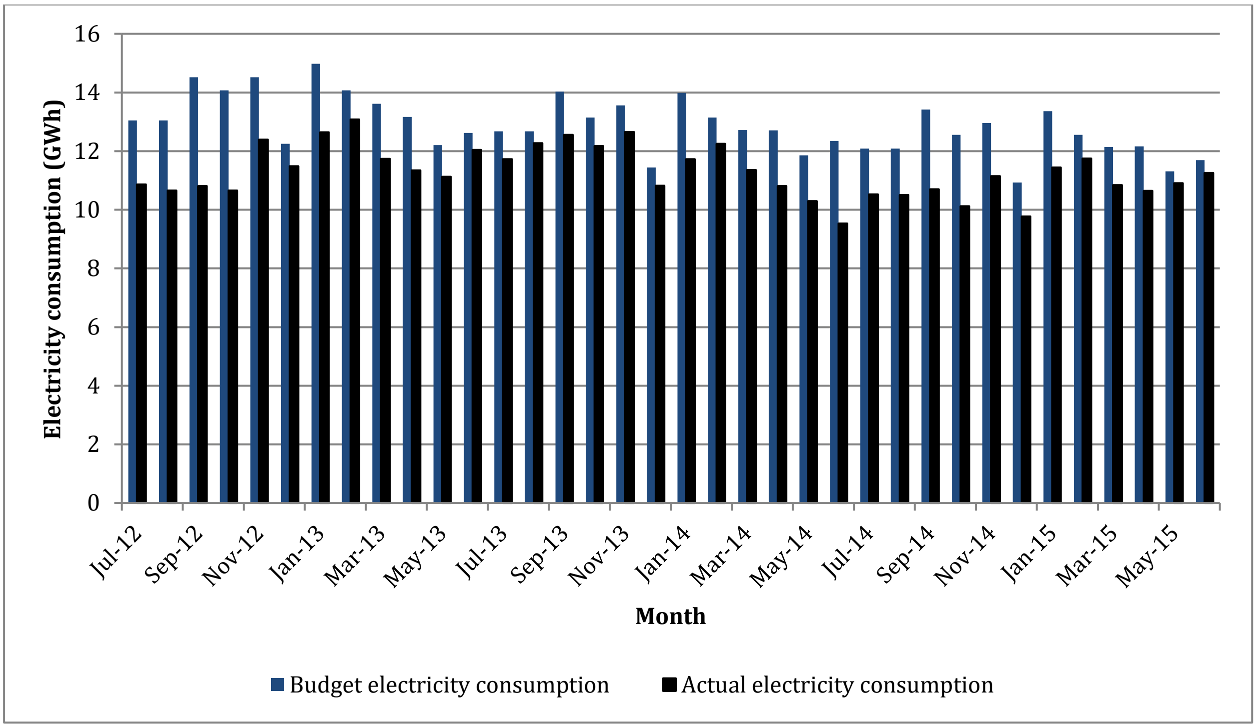


Figure 79: Comparison of monthly budget and actual electricity consumption for three-year period for Site 1, Shaft 1

Figure 80 shows the budgeted and actual electricity consumption for the systems of Site 1 for 2013 and 2014. In 2013, the error between the budget and the actual consumption was 8.5%. In 2014, this error increased to 14.6%. This is indicative of the fact that the electricity consumption budgets are not calculated accurately. As the graph also shows, the budgets are often not sufficiently adjusted year-on-year. The budgets only became marginally more accurate for three of the systems.

The second major problem with the existing methodology is that it provides only monthly total energy budgets. To provide further resolution, the group divided the total budget by the number of time periods in the month. However, as operations had varying electricity demands throughout the day, as well as on different days of the month, this method was highly inaccurate.

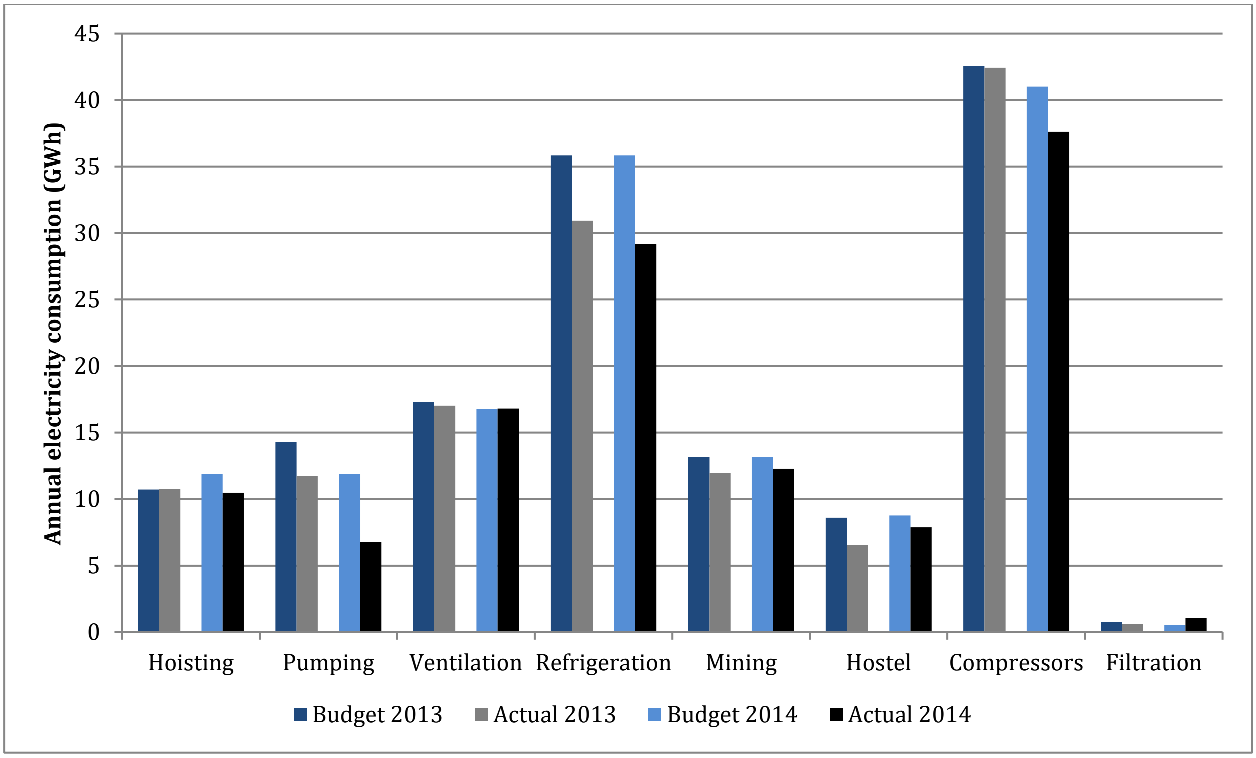


Figure 80: Comparison of budget and actual electricity consumption for the systems of Site 1, Shaft 1 for 2013 and 2014

The average weekday electricity demand for the compressed air system of Site 1, Shaft 1 is shown in Figure 81. The typical weekday electricity demand profile for a compressed air system has a pronounced peak around midday, marked as Point A in the figure. As production activities cease, and depending on whether energy saving initiatives are in place, electricity demand would reduce, as marked by Point B.

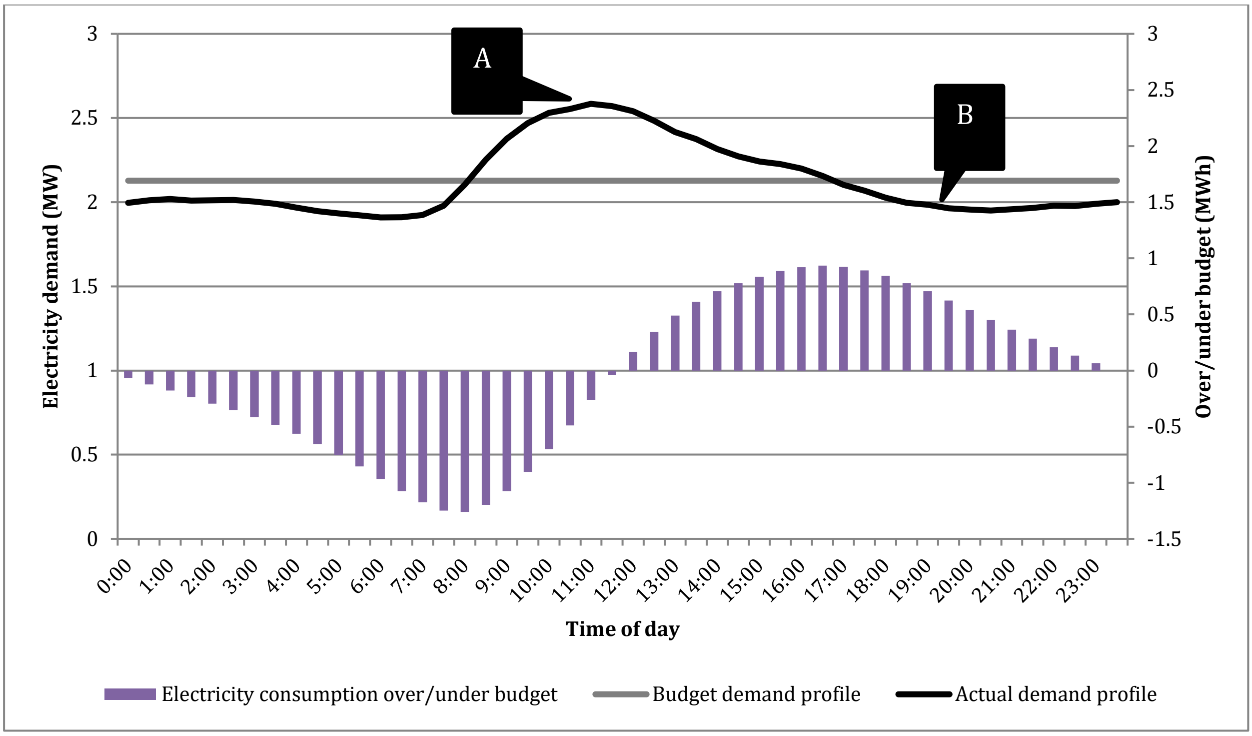


Figure 81: Site 1, Shaft 1 compressor system electricity demand profile for weekdays

This is shown graphically in Figure 82. In the figure, the budget electricity demand is shown by the straight black line, whilst an average of the actual demand for weekdays is shown as the curved red line. The actual cost for electricity for each time period is shown using green (off-peak), yellow (standard) and red (peak) bars. The budget cost profile is shown as a light gray overlay. As the graph shows, there is a major discrepancy between the two cost profiles.

In this case, the budgeted and actual electricity consumption for 24 hours was assumed to be equal (the budget was scaled to match the actual). However, even in such a case, the actual and budgeted costs differ from 1%–35% throughout the week at different half-hour periods. Over a typical week, this effect becomes even more pronounced. During low demand season, an error of 1.8%–9.6% is shown on a daily aggregated basis.

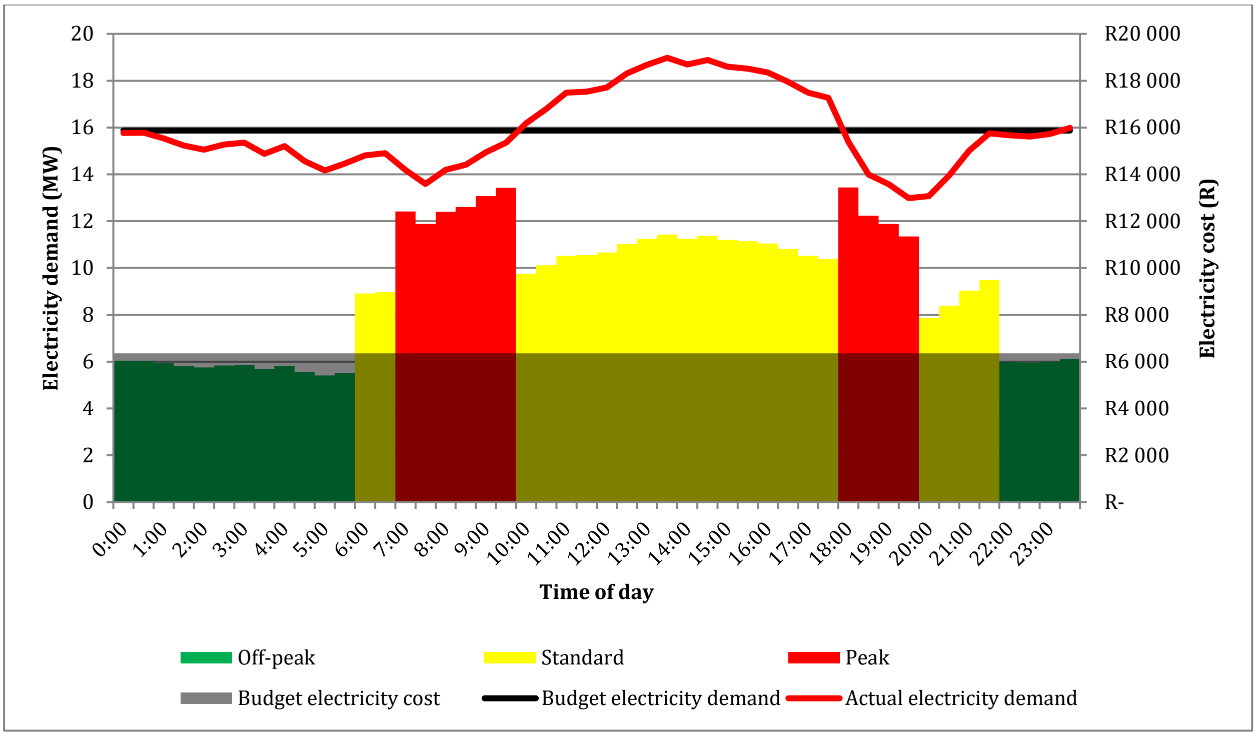


Figure 82: Comparison of budget and actual cost profile for Site 1, Shaft 1

Figure 83 shows the average total daily electricity consumption for Site 1, Shaft 1 for a one-month period. Consumption on weekdays is higher than over weekends because of the way production is scheduled on the mine. Typically, Sundays are non-production days. Operations begin ramping up early on Monday mornings, and only cease on Fridays. In some cases, mining may continue on Saturdays. This is typically the case when production targets for the week or month have not been met. As the graph shows, the average consumption profile also does not compensate for these production level changes throughout the week.

Public holidays also affect the consumption profile depending on whether they are used for production, as well as where they fall in relation to the weekend. For example, when a public holiday falls on a Monday, operations will often only resume on Tuesday morning.

Mines typically operate continually throughout the year under normal conditions. However, mining operations stop annually from approximately 24 December and start up again in January. During this long break, many of the mine’s HVAC systems may be shut down, such as the refrigeration plants, resulting in a much lower electricity demand than over non-working weekends.

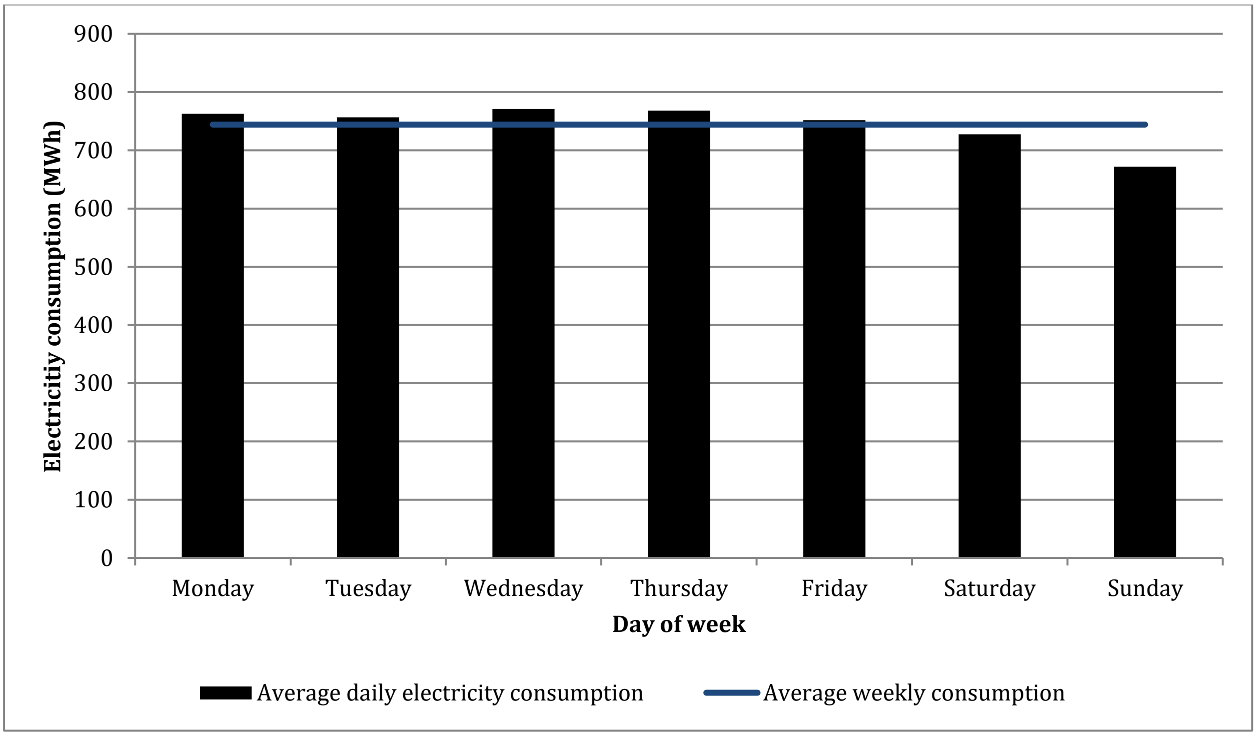


Figure 83: Average daily electricity consumption for Site 1, Shaft 1 for different weekdays

In terms of annual electricity consumption, another major role player is ambient temperature. During the cooler winter periods, surface refrigeration plants can be shut down. However, heating requirements in personnel living quarters would increase as temperatures decreased. The budgeting methodology implemented by the mine had already taken this into account.

A final major contributor to inaccurate budgets is that operational changes are generally not considered. During the budgeting process, estimates of electricity consumption were made based solely on the number of days in the month. This method would not consider the number of working and non-working days in the month. Changes to production levels were also not included during planning. The only operational change that was considered was the implementation of new DSM-funded energy saving projects.

As a result of these problems, the existing budgeting methodology was not conducive to operational energy management. In many cases, existing budgets were far too high, and even when operated inefficiently systems would not exceed them. Second, by not having sufficient resolution, the budgets were only useful at an aggregate level at the end of each billing month. During operations, the inaccurate budgets could not be used to determine what the actual performance of the operation was. As a result, mine personnel only discovered a problem towards the end of the month.

A new budgeting methodology needed to be implemented. This methodology would need to consider all significant energy drivers and operational changes. The budgets developed would have to be of sufficient accuracy, as well as provide sufficient resolution and daily, weekly and monthly electricity demand profiles.

4.4.2 Application of new budget methodology

The first part of the analysis and budgeting process is information collection. This information assists in informing the eventual energy usage model developed. The first information collected was a list of the electric motors on-site and linked to each system, as well as their expected operation levels. This information was collected during the previous phases of the case study. Next, the energy drivers linked to the systems were identified.

Using information for the entire mining group, an analysis was done to determine which macro factors played a significant role in driving energy demand. Table 30 shows the results from performing a statistical analysis of major potential energy drivers to GM Group 1. A correlation coefficient was calculated comparing the average monthly electricity consumption for the site with *inter alia* average monthly production, the depth of the operation, and the number of shafts and levels.

On the macro scale, production correlated well with increased electricity consumption. This correlation would appear to be logical as many of the mine's large electricity-consuming systems are linked to production. The depth of the mine was the next biggest correlating factor. This is likely due to the increased temperatures of virgin rock at depth, meaning that more support systems are needed to make working conditions safe. Finally, the number of underground levels present also showed some correlation to the electricity demand.

Table 30: Statistical analysis of macro energy drivers for GM Group 1[13]

	Average electricity consumption (Monthly kWh)	Average production (Monthly tonnes milled)	Mine depth (Ft)	Total number of shafts, sub-shafts and declines	Number of underground levels
Site 1	10 800 880	19 143	2 365	3	16
Site 2	15 816 969	50 210	2 000	2	16
Site 3	7 991 125	45 912	1 492	3	15
Site 4	52 830 482	75 650	3 000	4	26
Site 5	15 461 731	55 848	2 210	2	14
Site 6	22 061 644	50 897	2 426	4	14
Site 7	18 333 819	69 976	2 500	4	15
Site 8	26 246 335	82 619	2 161	2	17
Site 9	9 349 470	34 719	2 153	2	13
Correlation coefficient		**78%**	**48%**	**13%**	**39%**

From this aggregate analysis, it could be theorised that planned increases in production would be the largest contributor to an increase in electricity consumption. This was followed by an increase in the depth of the mine, followed by the number of underground levels.

However, following this analysis, a more in-depth analysis of the individual sites was done where the monthly production was compared with the monthly electricity consumption. Here it was found that the individual site level did not reflect the correlation between production and electricity demand.

Figure 84 shows the results of a regression analysis performed for the group. The total monthly tonnes milled was used in conjunction with the total monthly electricity consumption for a two-year period. As the graph shows, production correlated very poorly with actual electricity consumption. The highest R^2 value reported was 0.28, which would statistically indicate a poor model for predicting electricity consumption. This does not mean that the approach of comparing production to electricity use is not useful for analysing past performance, but only that it cannot be used to develop a model of what future use will be.

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[13] Site 4 was not included in the statistical analysis for Table 30. This is because it acted as an outlier, causing an artificial improvement in correlation between drivers and electricity consumption.

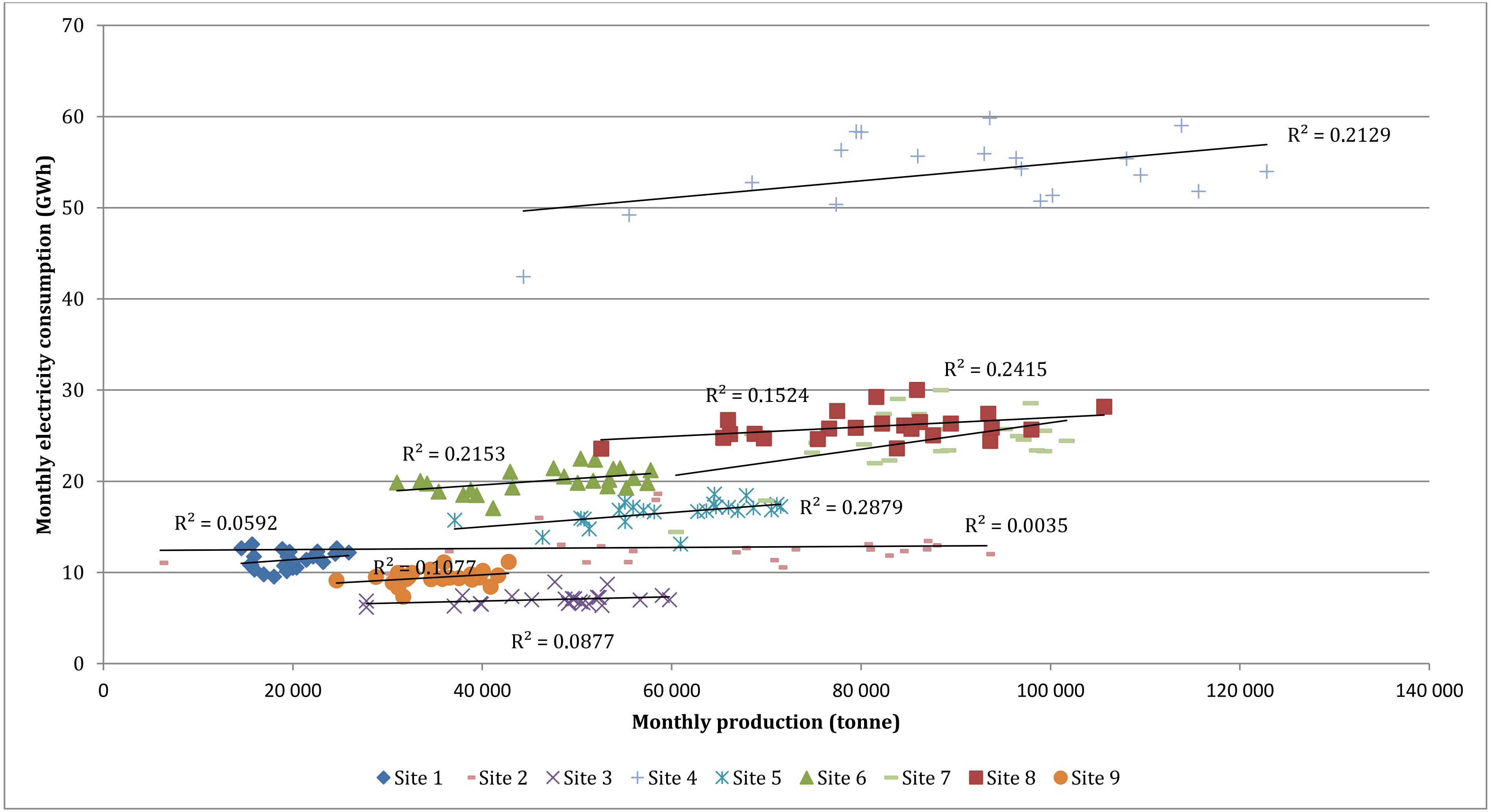

Figure 84: Regression analysis for GM Group 1 operations comparing monthly production with electricity consumption

There are several potential causes. First, although the mine's systems support production, very few are directly linked. In other words, the system must be present for the mine to operate, and its size is matched to the mine's total production. But, these systems are not linked to production on a day-to-day basis.

Many of these systems can also only be scaled down to a certain point when production activities are not taking place. For example, fans typically operate continually throughout the day and year to prevent hazardous gas build-up. However, another potential cause is that the system is not currently being managed properly. This could mean that the systems are operating during periods where they need not be.

Next, the typical systems present on a gold mine were analysed. A summary of the main systems on most of GM Group 1's operations is shown in Table 31. The energy drivers that were identified are also shown in the table. Constant energy drivers are drivers that are unlikely to change unless significant changes are made to the operation such as closing levels or mining deeper. Variable energy drivers are drivers that are expected to change continually.

Table 31: Summary of typical sub-systems present on South African gold mines

System	Constant energy drivers	Variable energy drivers
Winders		Skip weights, frequency of hoisting, mining depth
Dewatering pumps	Head height	Water demand, fissure water
Refrigeration plants	Temperature output	Water temperature in, air temperature and humidity, chilled water demand
Compressors		Compressed air demand, ambient temperature and air pressure, network air pressure set point
Ventilation fans	Mining activity	
Hostels	Holiday periods	Ambient temperature
Underground mining		Production

In the next section, each system will be discussed in more detail. The operation of the system will be briefly described. Following this, different energy drivers will be identified and explained.

Winders

The winder systems are usually subdivided into man and material winders, which are used to transport mine personnel and equipment underground, and rock winders, which hoist the ore up to surface. In some cases, the two winder types are combined.

The man and material winders are typically only slightly influenced by the mine production levels, and are more closely linked to whether mine shifts are occurring. As such, historical data can be used to reasonably model the energy requirements for the man winder.

Rock winders, however, are linked more directly to the production output of the shaft. Most rock winders have counterweights. As a result, a large proportion of electrical energy is consumed when starting the winder [100]. Vosloo [100] and Vergne [101] both indicate that the distance and mass hoisted have an effect on the power consumption of the winder. As such, the total product tonnes to be hoisted as well as the depth of mine activities must be considered when modelling the winder system.

Historical energy usage profiles must also be considered as winder systems can be optimised to run outside of peak periods [102], [103]. Figure 85 shows the average weekday electricity demand for the winder system of Site 7, Shaft 1. The solid black line shows the winder electricity demand profile for July 2015. During this month, the evening peak periods (17:00 to 19:00) were actively being avoided. However, by November 2015, this was no longer the case (grey dashed line).

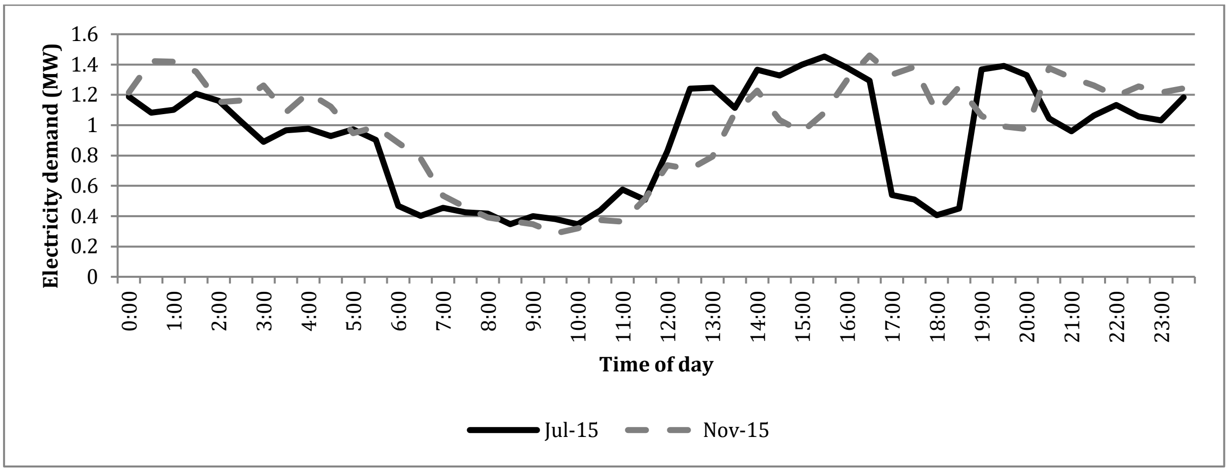

Figure 85: Weekday average electricity demand for the winder system of Site 7, Shaft 1

Dewatering pumps

Dewatering pump systems are large energy consumers in most South African gold mines. This is due to fissure water seeping into the mine, as well as chilled water transported underground to support operations. While not directly related, the production quantity of the shaft does play an important role in determining the pump system’s energy needs. This is because additional chilled water is often required at the stope[14] area where production is taking place. As such, increased production may increase chilled water demand underground. This water collects in underground dams along with fissure water, and must be pumped to surface to avoid flooding the mine.

Pumping systems are also often optimised to run outside of peak periods as underground dams provide storage buffers. As such, pumping system historical energy usage profiles must be considered. Figure 86 shows the average weekday electric power profile for the pumping system of Site 5, Shaft 1. Both the low demand (black line) and high demand (grey line) seasonal profiles are provided. As the graphs show, the pumping system has been optimised to not operate during peak periods (indicated as the shaded areas).

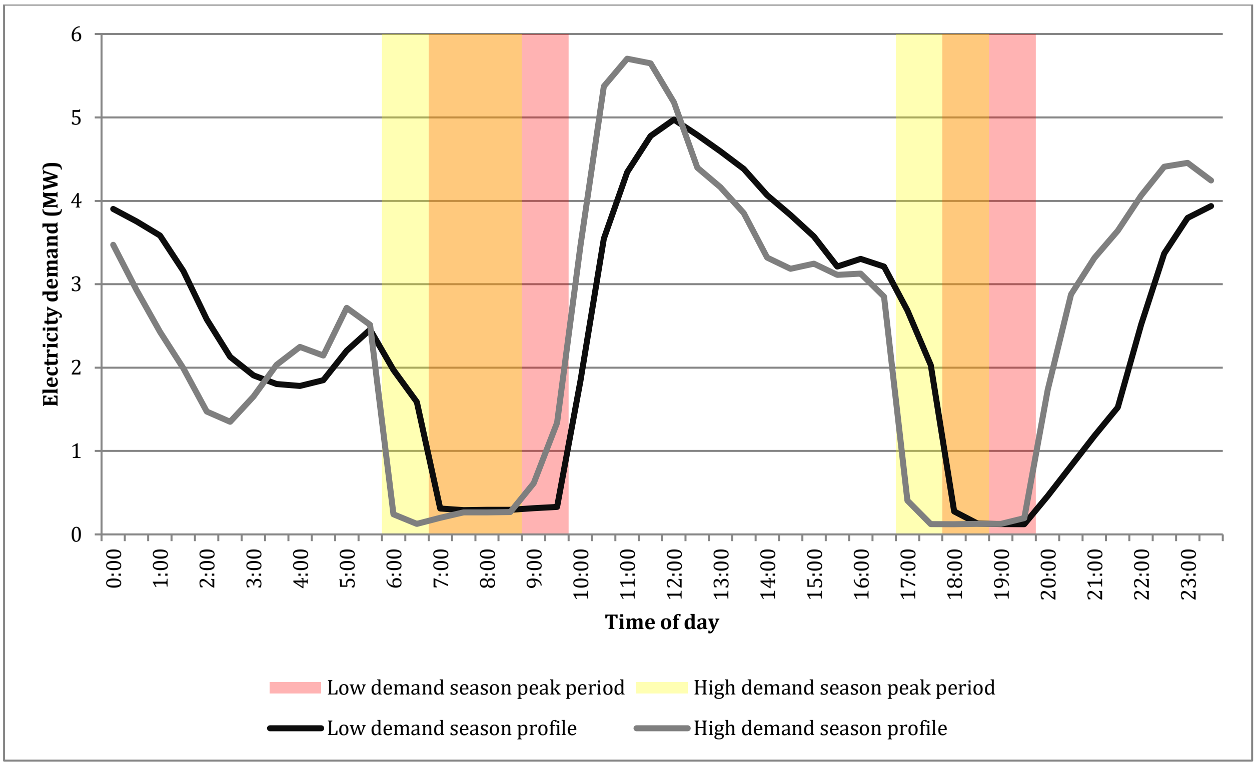

Figure 86: Average weekday electric power profile for Site 5, Shaft 1 pumping system

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[14] The stope area refers to the area where drilling and blasting is actively taking place on the respective underground mine levels.

Refrigeration plants

Refrigeration plants typically cool water for use underground to around 2 °C [55]. This is done to reduce underground temperatures to safe levels [104]. Without chillers, the temperatures in South Africa's deep underground mines would not allow for humans to work safely.

Several different refrigeration systems are typically used, namely, surface refrigeration plants, underground refrigeration plants, and ice plants [105]. Three energy drivers are important for these systems. The first is the ambient temperature, which changes through the day and year. During colder months, it is common for surface refrigeration plants to be switched off entirely. Secondly, production increases or decreases might increase or decrease the demand for chilled water. Finally, as mining depth increases, higher quantities of cold water will be required to maintain safe working conditions. In some cases, it becomes necessary to install entirely new water chilling systems underground.

Figure 87 shows the total monthly power consumption for the refrigeration system for Site 5, Shaft 2. Also shown are the average minimum and maximum temperatures for each month in South Africa. As the graph illustrates, the power consumption declines significantly during the colder months. This is due to the refrigeration plants being shut down when ambient conditions already provide sufficiently cold water to be sent underground.

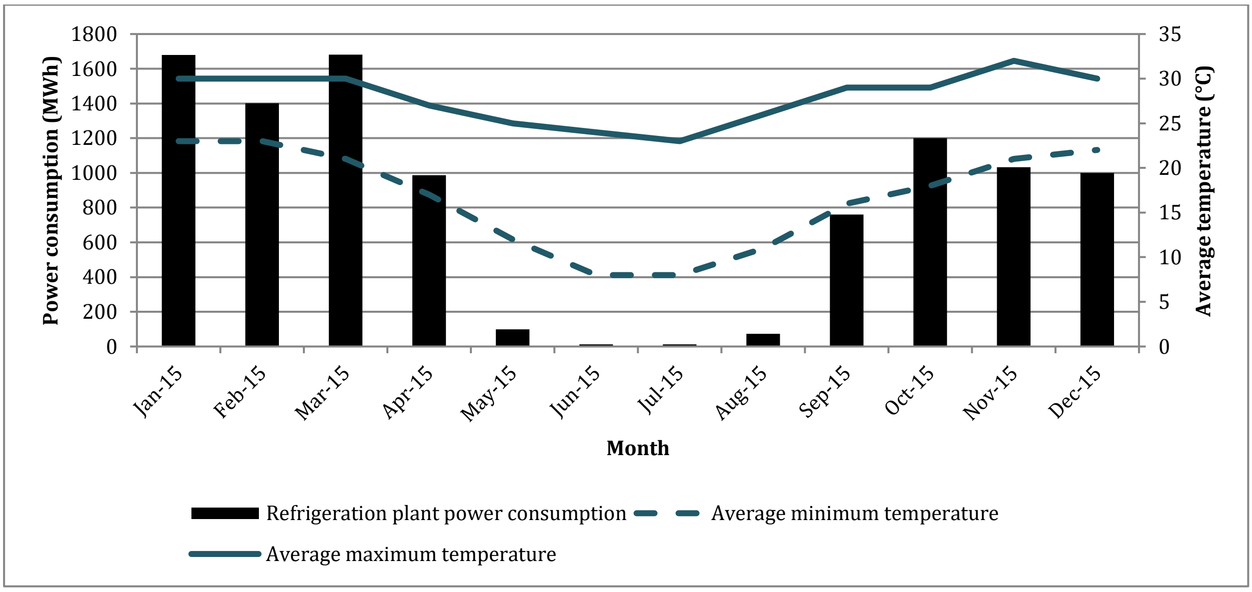

Figure 87: Monthly power consumption and average temperature for refrigeration system for Site 5, Shaft 2

Refrigeration plants are often the target of load-shifting or peak-clipping DSM projects, meaning that they are shut down during peak periods when available water allows. This means that daily historical usage patterns must be considered.

Compressors

Compressed air is used as an energy carrier on mines [106]. This is done due to the ease of transport and inherent safety of using compressed air instead of electricity [96]. The majority of pneumatic equipment used underground, such as rock drills [106] and loaders [97], in the mine are directly linked to mine production.

As production increases, this equipment will be used more, or more equipment will be added. Thus, as production increases or decreases, compressed air demand and therefore electricity demand will increase. An exception to this is the refuge bays installed underground for use during emergencies. As such, production volume is the most significant contributor to energy consumption of compressed air systems.

Another ad hoc factor that should be considered where needed is adding equipment that requires a higher operating pressure to the network. Further, the pressure of the compressed air network is often managed throughout the day. This is because some equipment, such as pneumatic loaders, have a higher operating pressure than others, such as refuge bays. Outside of drilling shifts, some of this equipment is not needed, meaning that the pressure of the compressed air network can be reduced. This will result in a decrease of electrical load. This has been the subject of serval DSM projects within the group.

Figure 88 shows the average weekday compressed air flow demand and network pressure for Site 4. The network pressure set point is set to a lower value (≈360 kPa) during evening peak whilst no drilling is being done. This also coincided with a reduction of compressed air flow to the shaft. As a result of these interventions, the compressed air system electricity demand was reduced by 2.1 MW for this period.

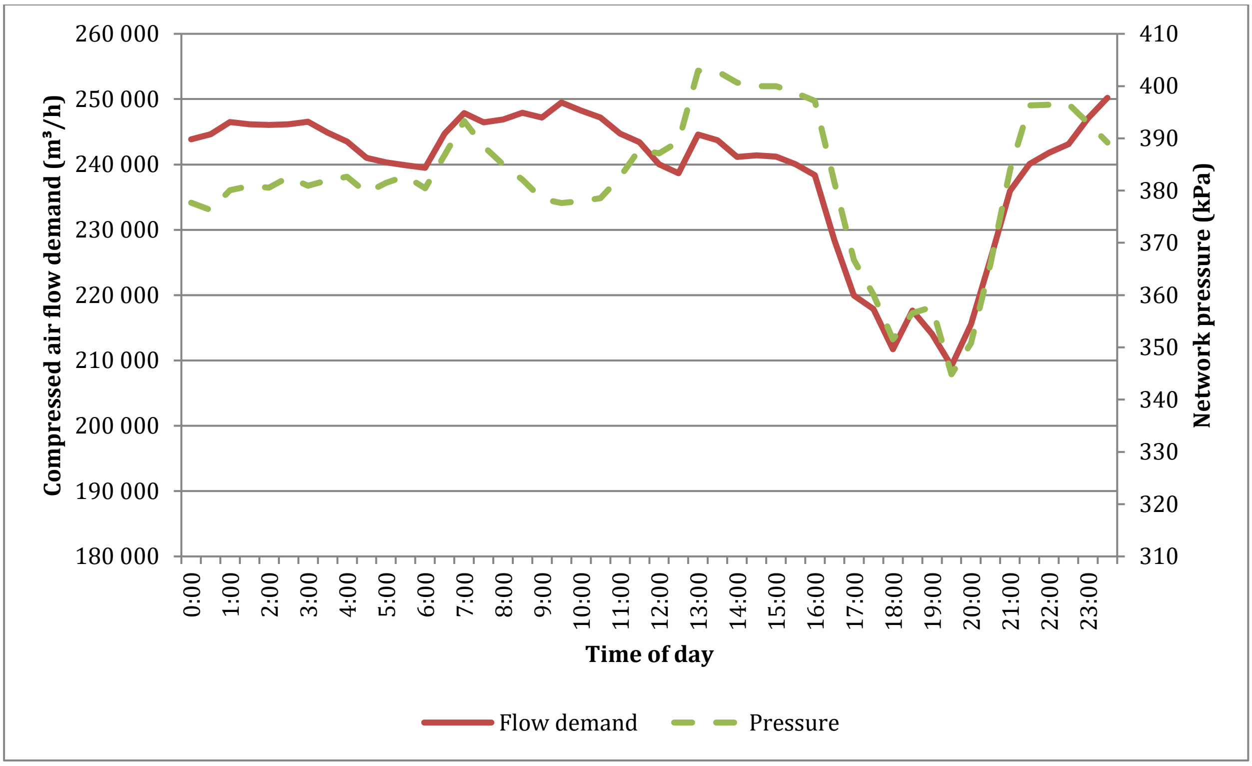

Figure 88: Average daily compressed air flow demand and network pressure for Site 4

Ventilation

Ventilation fans are used in conjunction with bulk air coolers to cool mines underground and provide safe working conditions. These fans also often serve the purpose of preventing methane gas build-up.

Ventilation fans are often operated as baseload equipment. This is due to the risk of methane gas build-up if they are switched off. However, changes in production volume either over a long period or throughout production shifts might act as a driver of the fans. On some mines, variable speed drives or capacity of ventilation allows for ventilation fans to be shut down during peak periods. This is usually only done in the evening, when most personnel are not present in the mine.

Throughout the group, a peak-clipping project had been implemented on the ventilation systems, resulting in a small electricity demand reduction during evening peak. As a result, the ventilation systems throughout the group had a stable profile, with only a slight change to the profile during evening peak periods.

Housing and hostels

These smaller energy consumers house mine personnel. Ambient temperature is the most significant energy driver as heating equipment is operated during winter months. Energy usage also typically follows a distinct profile, with peaks coinciding with the end of mining shifts.

Figure 89 shows the monthly total electricity consumption of Site 4's hostels. Also plotted on the graph is the South African average monthly maximum and minimum temperatures. The electricity consumption of the hostels increases as temperatures decrease. This relationship is the inverse from what was seen regarding refrigeration plants (as shown in Figure 87).

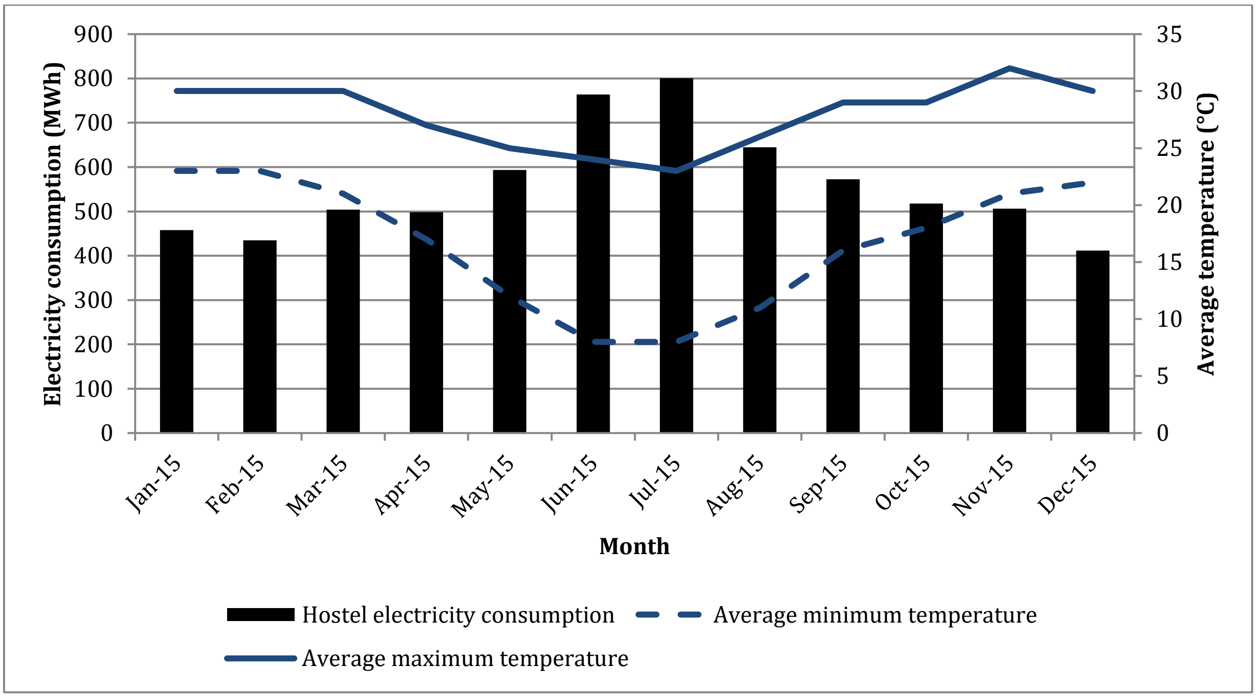

Figure 89: Monthly total electricity consumption for Site 4's hostels

Other considerations

An important consideration for all systems is their respective operating efficiencies. Mining equipment typically requires regular maintenance, as well as overhauls and replacement from time to time. As system efficiency deteriorates over time, this must also be considered during the budgeting process.

Implementation of new energy management initiatives must also be considered. As these initiatives affect energy consumption, they must be considered in the budget.

Finally, planned operational changes should also be incorporated into budgets. New levels added to the operation, as well as increased mining depth, will increase overall electricity demand. This should also include motor changes, planned shutdown of parts of a system, as well as new components being commissioned.

Adaptive budgets

It is important that budgets can adapt to changing circumstances on the mine. For this reason, a whole-year budget should be developed prior to the start of the financial year (typically required for the financial department). This budget should then be adjusted on a month-to-month basis. This will ensure that when control philosophies change, the budgets remain up to date.

Due to their seasonality, this approach may not be suited to refrigeration and hostel systems. In both these cases, the budget should be based on the previous winter's historical data. As Figure 90 shows, a three-month historical period should be used based on months from the same season.

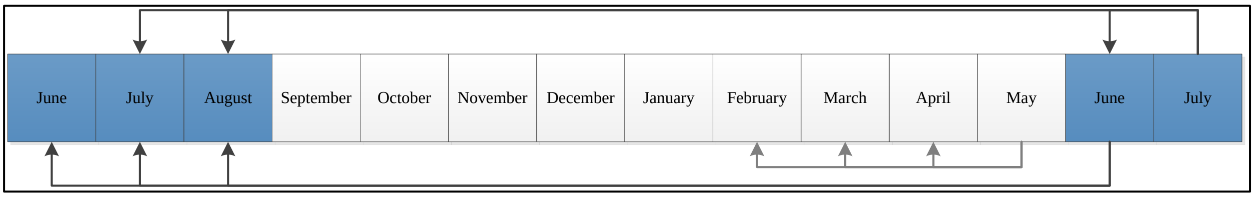

Figure 90: Budget development based on historical data for seasonal systems

Bottoms-up approach

Finally, it is important that the budget for the total facility be constituted from the budgets of the different sub-systems. On some mines, this approach is reversed, with a total mine budget being developed first and then split proportionally. This approach will result in inaccurate budgets on the system level. Instead, the total budget should be calculated based on the sum total of all the underlying system budgets. Where there is a gap between total electricity demand and measures systems, a budget can be calculated based on the difference.

4.5 Feedback

The basic methodology for developing feedback for GM Group 1 is shown in Figure 91. The process follows a sequence of steps, starting with information collection. Once a feedback structure has been implemented, it must be continually evaluated to ensure that it remains effective at achieving operational energy management.

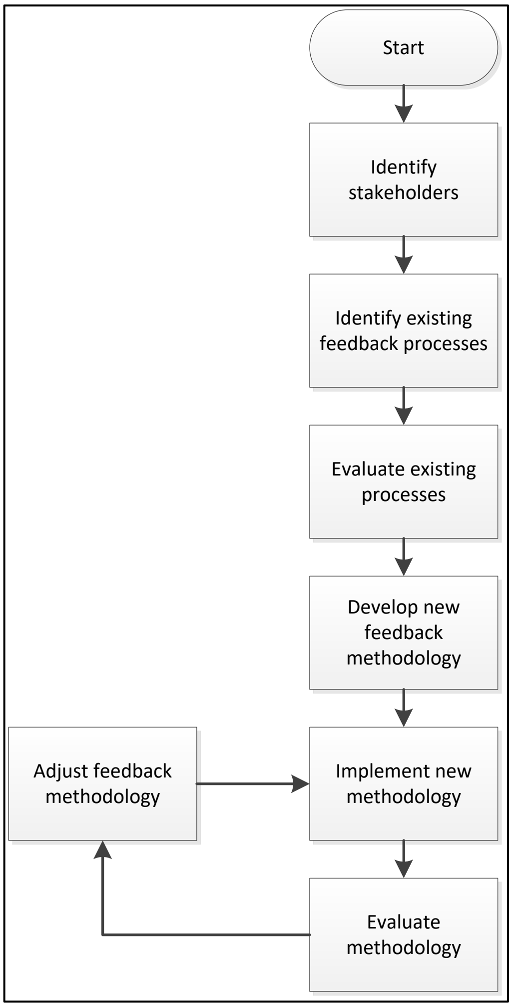

Figure 91: Feedback development process for GM Group 1

The first step in the process is identifying key stakeholders. Broadly speaking, stakeholders could fall into one of three categories for GM Group 1. The first group consists of people who primarily require feedback for informational purposes. This group would not act directly to improve energy performance. For example, the chief executive officer (CEO) falls into this group who requires feedback on whether group energy policies are effective. The second group consists of energy management personnel who are responsible for managing energy use throughout the group. The final group encapsulates operational personnel such as control room operators. This group has the most direct influence on energy performance.

Figure 92 illustrates the stakeholder categories and the flow of information and control throughout the group. At the executive level, information is highly summarised. The executive influences the layers below by altering company policy and strategy towards energy. At the energy management level, more processed data is available. The energy manager has two mechanisms for affecting energy change – implementing energy projects or driving initiatives and awareness, such as operational energy management.

Control room operators have the most direct influence on powered systems and their energy performance. However, at this level, information available is typically raw and unprocessed.

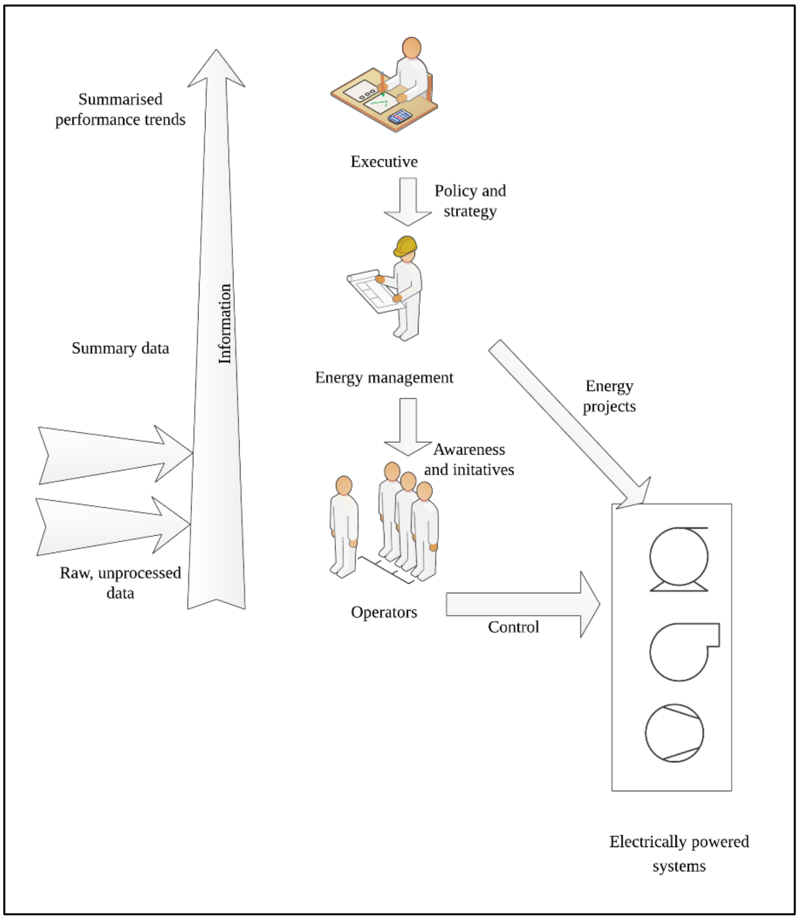

Figure 92: Information and control structure for GM Group 1 energy management

Figure 93 shows the stakeholder structure for GM Group 1. In this group, energy management formed part of the engineering department’s responsibilities. A single energy manager was responsible for the entire group’s energy usage. Electricians responsible for the different business units were assigned to assist with energy management activities. However, these personnel also had other responsibilities.

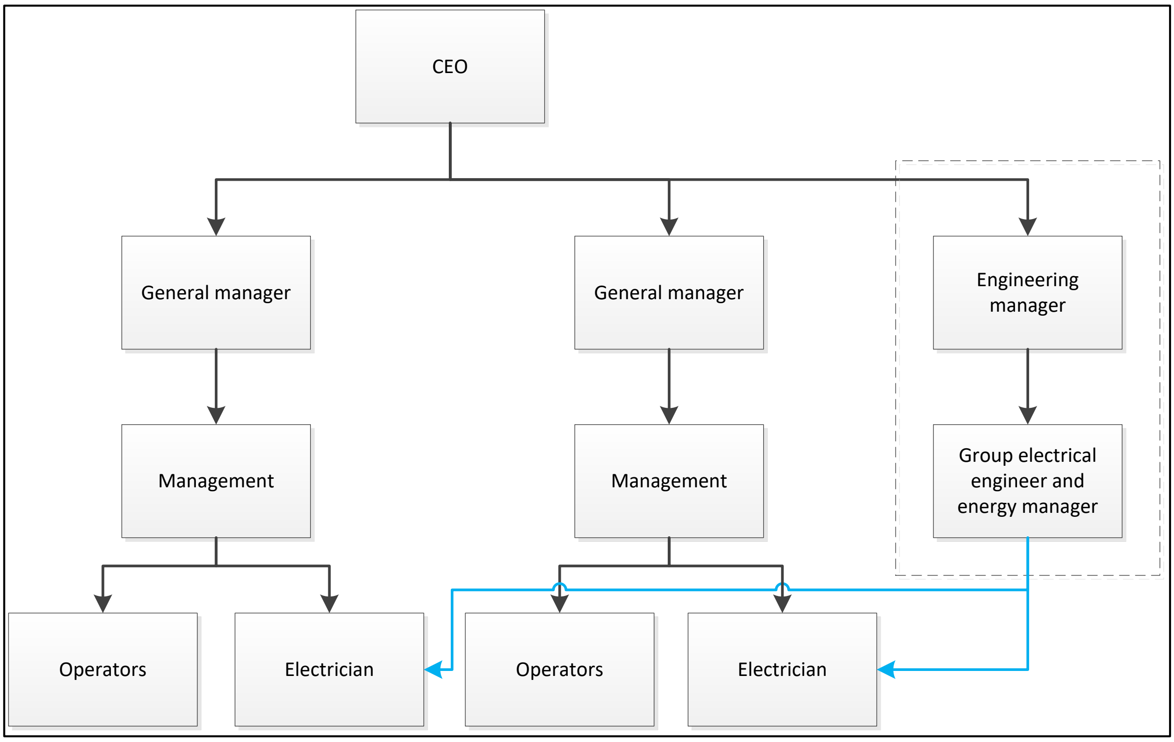

Figure 93: Stakeholder structure for GM Group 1

Feedback was provided to the energy team via automated weekly energy reports. The reports showed a breakdown of the different energy-consuming systems, as well as their performance against budgeted energy consumption. An example report is included in Appendix A. The energy reports were discussed monthly with the group energy manager and electricians. The feedback development process also included receiving feedback from mine personnel on the reports, such as requests and recommendations.

Another form of feedback was provided through screens in control rooms. An automated energy management system monitored operations, and could notify operators when the system was deviating from optimal efficiency. This was done in the form of an on-screen alarm.

Finally, mine personnel also received daily reports on the performance of system where energy management interventions had been implemented. These daily reports were primarily aimed at ensuring the sustained performance of the interventions. Whenever an intervention underperformed, all stakeholders were informed within 24 hours so that corrective action could be taken.

Chapter 5 Case study – Results

5.1 Overview

This chapter will serve as validation of this study. This will be done by evaluating the effectiveness of the implemented methodology. In this section, the cost saving results achieved will be discussed. The results of the measurement verification and analysis methodologies have already been presented and discussed in their respective sections. Therefore, they will not be repeated here.

First, specific instances where the operational energy management lead to an impact will be discussed. This will serve to illustrate the mechanisms that make it an effective method for improving energy performance. Next, the energy performance for the entire GM Group 1 will be analysed. This will provide a more general indication of the effectiveness of the system.

5.2 Results from improved budget methodology

The improved budgeting methodology was verified using data for 2014 and 2015. Data from 2014 was used to develop budgets for 2015. Table 32 shows a summary of the difference between the actual electricity consumption for 2015, the budgets developed by mine personnel and the new budget methodology. As shown, the accuracy of the budget improved, with the difference for electricity consumption decreasing from 16.5% to 1.98%.

Table 32: Difference between actual values and existing group budgets with improved budgets

	Electricity consumption	Cost
Existing budget	16.50%	47.42%
New budget model	1.98%	14.14%
Improvement	**14.52%**	**33.28%**

The accuracy of the budget in predicting costs on a half-hourly, daily and weekly basis also improved by 33.28%. It should be noted that this does not reflect an error by the mine in budgeting for electricity costs on an aggregate (monthly) level. Rather, this indicates an improvement in budgeting for costs during the progression of a workday and week. For the aggregate level, the improvement coincided in magnitude with that of electricity consumption.

Figure 94 and Figure 95 show a breakdown of the average error for the existing budget methodology compared with the new budget methodology. The grey bar shows the existing methodology in use by the mine. The black bar shows the basic new methodology, which does not incorporate new data as the year progresses. Typically, this is the budget that would be used for financial budgeting purposes prior to the start of the year. The red bar shows the final model, with progressive adaption included.

Figure 94 shows a breakdown by system. The largest and most consistent improvements were made in systems that tend to follow a fixed profile, such as fans and mining. Systems which tend to be more volatile show less improvement with the basic model, and a significant jump to the adaptive model. This is shown by systems such as hoisting, compressors and refrigeration.

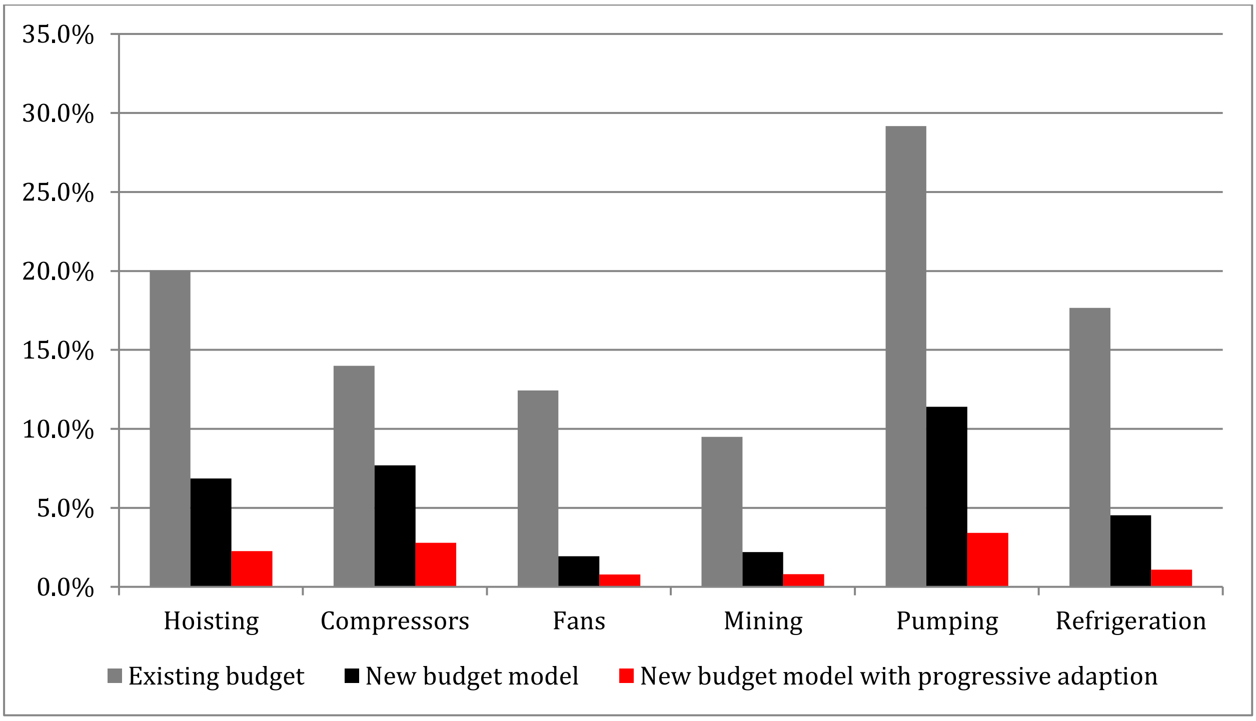

Figure 94: Comparison of budget model errors for GM Group 1 by system

The poorest performance shown by either model was for the pumping system. This was caused in part due to a change in tariff structures in 2015, where Eskom evening period were moved one hour earlier during high demand seasons. As nearly all the pumping systems in the group form part of DSM projects which avoid these peak periods, the control of the systems was adjusted to compensate for this. While this change in profile was anticipated while developing the budgeting methodology, there was no way to accurately predict what change would take place based on historical data. To do so, a simulation model would have been required.

Figure 95 shows a breakdown of the new budgeting model's performance aggregated by site. An improvement was seen on every site throughout the group. The basic model outperformed the existing budget on 89% of the systems in the group. The adaptive model outperformed the existing model 100% of the time. This indicates that the improvement was not an improvement on average, but rather an actual improvement for each site and system. It can therefore be concluded that the improved methodology consistently outperformed the old methodology.

This shows conclusively that the improved budgeting methodology was more accurate than the existing methodology.

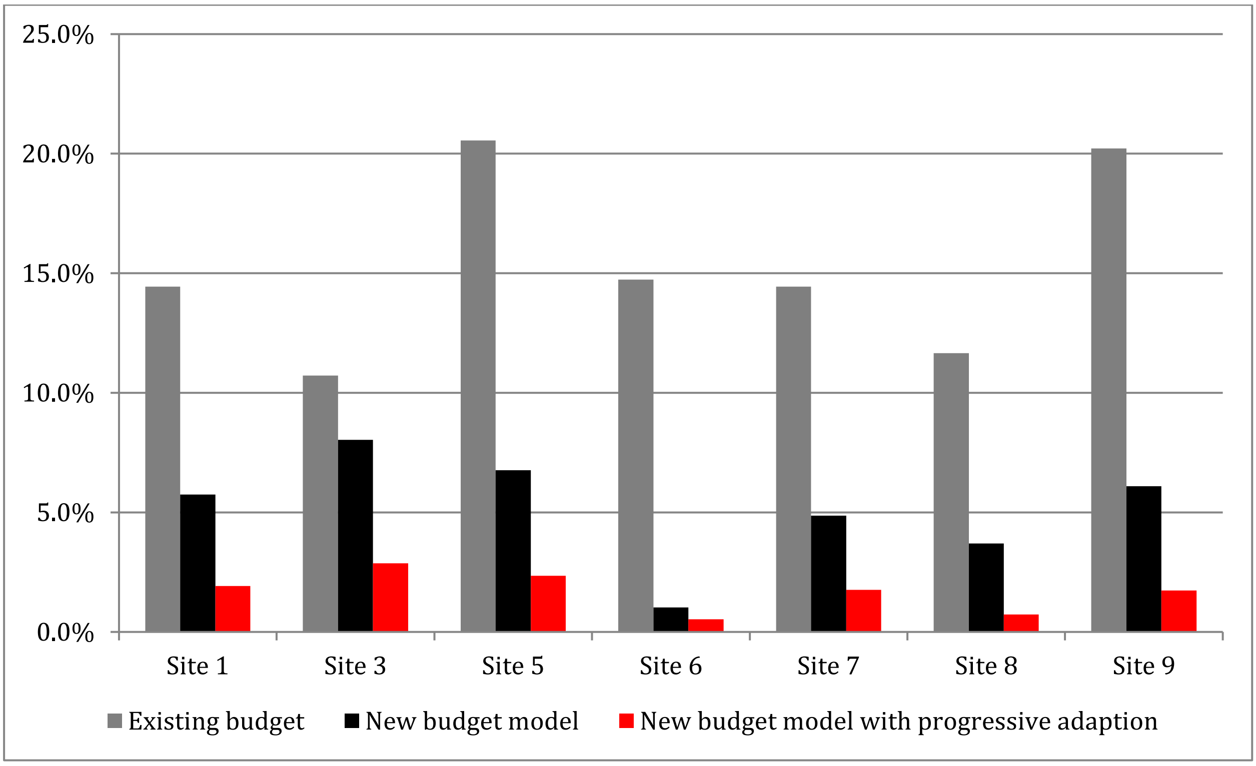

Figure 95: Comparison of budget model errors for GM Group 1 by site

5.3 Specific results

5.3.1 Site 3 ventilation fan

In March 2016, an additional ventilation fan was started on Site 3. This was an unplanned and unbudgeted start-up, and was done because of problems underground. Due to feedback provided as part of operational energy management, this non-conformity was quickly identified and brought to the attention of mine personnel. Upon detailed investigation, it was found that the start-up of the additional fan had not alleviated ventilation problems underground, and was purely wasting electricity. The ventilation fan was shut down in June 2016.

Figure 96 shows the daily total electricity consumption of Site 3's ventilation fan system in blue, and the system budget in a light grey overlay. As the graph shows, initially the system operated within budget at a relatively constant daily consumption. In March, an additional fan was started. This fan was identified as being an unnecessary waste, and was shut down at the end of June.

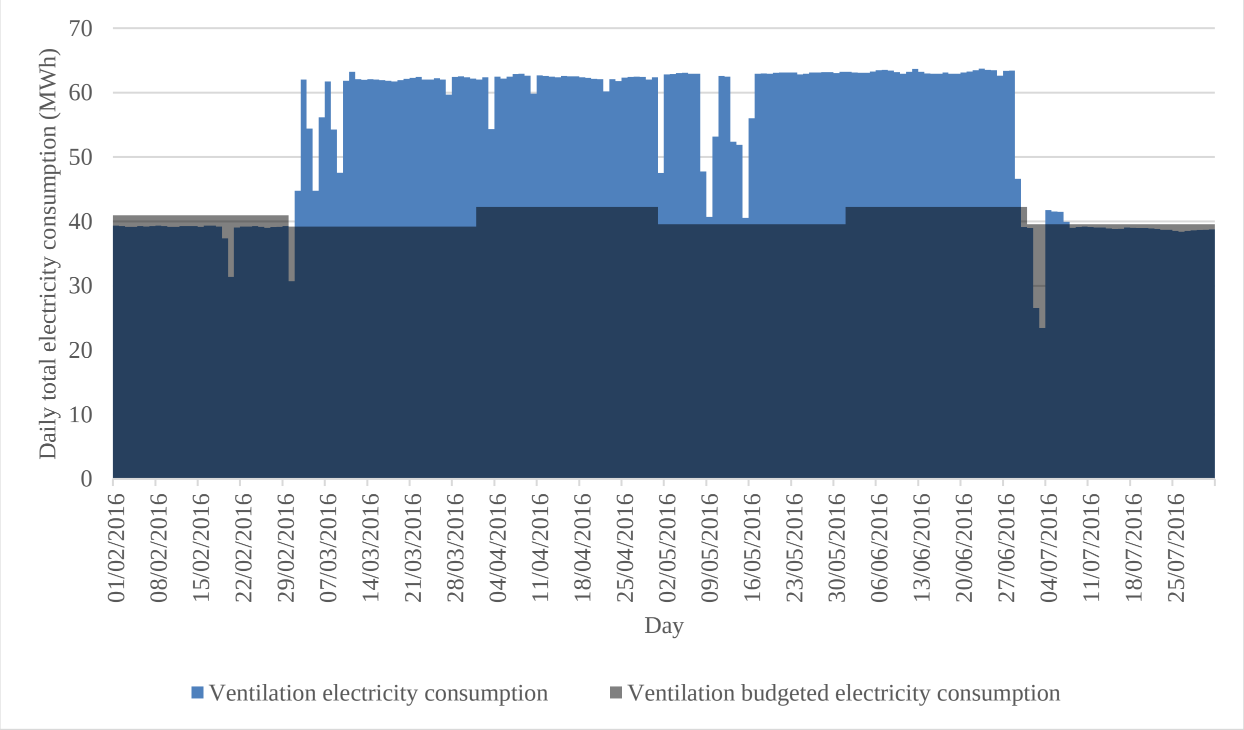

Figure 96: Site 3 ventilation fan daily electricity consumption from February to July 2016

The additional electricity demand due to the unnecessary ventilation fan was 1 041 kW. The additional annual electricity consumption, had operational energy management not identified the non-conformity, would have been 9.12 GWh. The equivalent cost saving is R6.39 million.

5.3.2 Site 4 ventilation fan

In January 2017, it was noted as part of an operational energy management feedback report that the electricity consumption for Site 4’s ventilation had increased to nearly double the regular consumption. Upon investigation, it was found that an additional fan had been started without alerting the site engineer.

The additional fan had been started after a blocking wall had collapsed underground. This wall had been put in place to block off airflow to an adjacent mine to which some of the underground levels were connected. Once the wall had collapsed, airflow to Site 4’s underground sections beneath the level where the connection had been made had decreased, which led to the fan being started.

When it was started, the electricity consumption of the additional fan had not been considered. However, as part of the feedback, the increased cost of running the additional fan could be quantified and reported. Due to this high cost, the rebuilding of the wall was prioritised, and the additional fan was shut down on 8 February 2017.

The daily total electricity budget and actual consumption is shown in Figure 97. Also, shown in the graph is the cumulative sum of the difference between the actual and the budget electricity consumption. As the cumulative sum line shows, the average difference was close to zero during the lead up period under normal operating conditions. However, once the fan was started, the deviation was quickly detected.

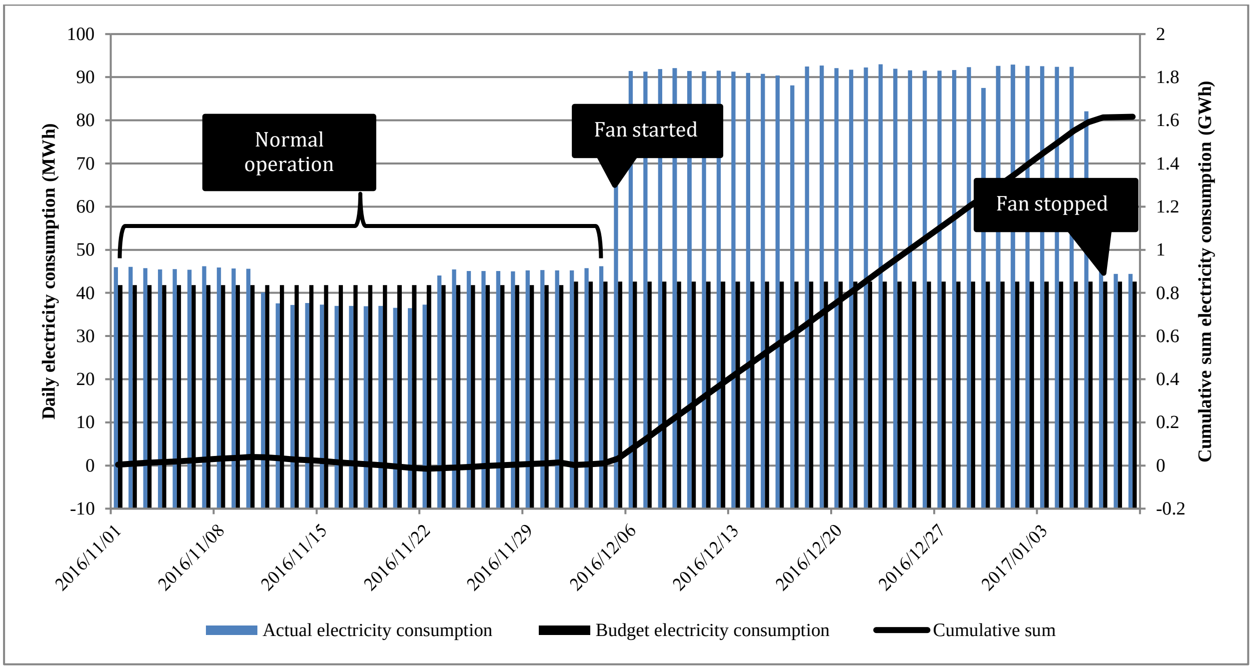

Figure 97: Daily total electricity budget and actual consumption for Site 2 ventilation fans

In total, 1.6 GWh of electricity was consumed due to the additional fan being necessary. This equates to a cost of R1.1 million for the 35-day repair period. The average daily cost of the additional fan was R32 300 per day. By providing this feedback, the actual daily cost of the collapsed wall could be determined, and additional motivation could be given for repairing it as quickly as possible. In similar cases, this can also assist in even motivating contractors to perform the work, as the high cost of a contractor can often be exceeded by the even higher wasted electricity cost.

5.3.3 GM Group 3 compressed air network

An energy saving initiative had been applied to the compressed air distribution network of a mineshaft of GM Group 3. This project was dependent on the cooperation of mine personnel, especially regarding continually monitoring the performance of the project to maintain cost savings. Although the project performed well, an additional energy feedback strategy was implemented to improve performance.

Feedback was developed and sent to the on-site project champion. Specifically, the feedback contained analysed data regarding the performance of several underground valves according to the initiative’s control philosophy. As these underground valves are often damaged by underground conditions or tampered with by underground personnel, they were one of the primary causes of reduced project performance.

The feedback report presented the project champion with a breakdown of each valve's adherence to the target set point. A valve that operated within 10% of the set point was marked green, whilst valves that exceeded the set point were marked red. As a result, the project champion could quickly identify the causes of reduced performance and intervene.

The feedback report was introduced in February 2015. Since the inception of the report, a clear increase in project performance can be seen, as shown in Figure 98. The figure also shows the average performance of the project prior to and after feedback was implemented. Overall, an additional average energy efficiency of 0.94 MW was achieved – a 19% increase in performance. This resulted in an additional annual cost saving of R5.8 million at 2016/17 tariffs.

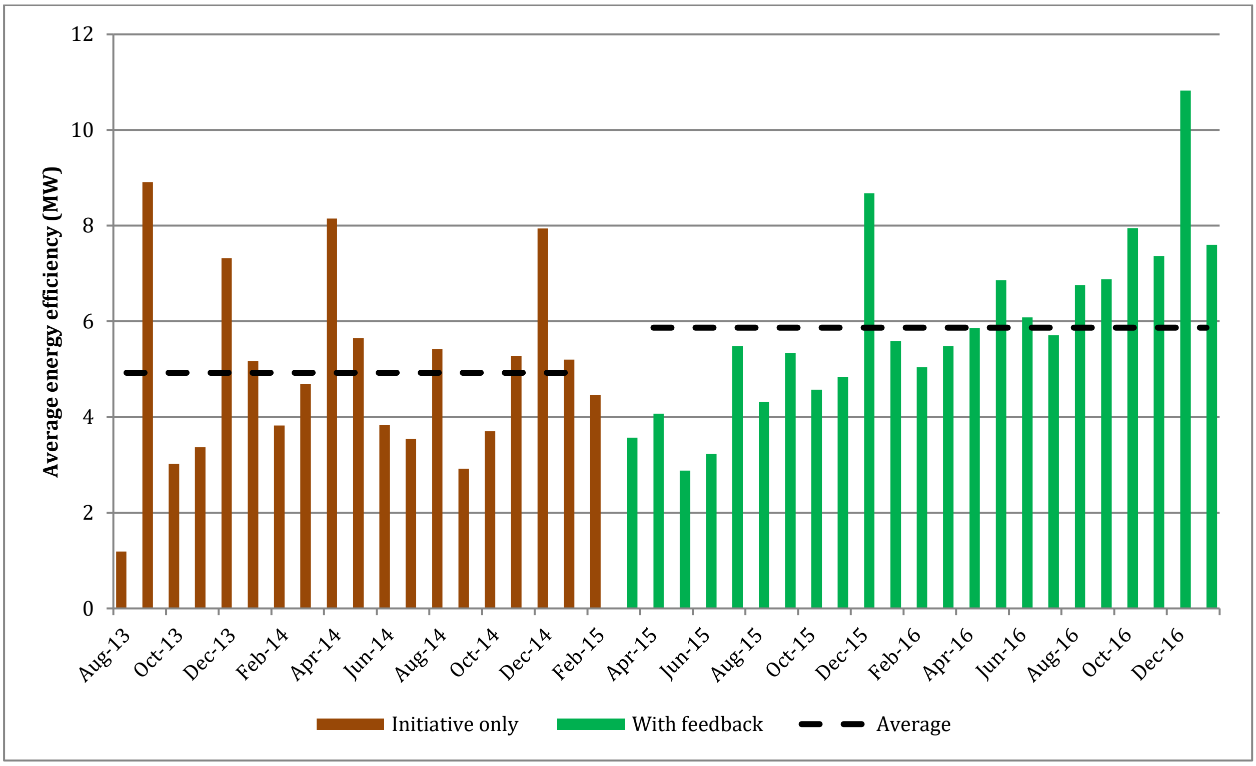

Figure 98: Monthly average performance of energy saving initiative

5.3.4 GM Group 3 mineshaft

On 24 January 2014, a feedback report was developed and implemented at GM Group 3. This high level, highly summarised report was intended to identify sites and systems within the group which were over- and underperforming in terms of energy budgets. An example of this report is included as Appendix B. Initially, the report was distributed to personnel at the different shafts and plants within the group. The group reported some positive impact from the report after implementation.

To improve the impact of the report, it was decided to include the chief financial officer (CFO) as a recipient of the report. By including this key stakeholder, additional priority was added to energy management. This was because the CFO was keenly aware of the budget constraints the group was experiencing at the time, and the implications of additional unplanned electricity expenditures.

One specific shaft was consistently exceeding its budget when the report was first implemented. Following the implementation of the report, performance did improve. However, the inclusion of the CFO as a recipient of the report resulted in the CFO contacting the shaft personnel and impressing upon them the importance of meeting the budget. Following this, the shaft's performance improved dramatically.

The results of implementing the feedback report are shown in Table 33. As the table shows, implementing feedback led to an approximate saving of R8.8 million per annum. However, by including key stakeholders in the report, this savings increased to R29.7 million per annum.

Table 33: Performance impact of daily feedback report for GM Group 3

Stage	Performance vs budget	Average daily cost of excess electricity	Annual savings (vs no feedback)
No feedback	39.9%	R81 934	–
Feedback report	30.7%	R57 744	R8 829 206
Feedback to key stakeholders	0.4%	R583	R29 692 946

5.3.5 Summary

The examples in this section served to illustrate the effectiveness of operational energy management in achieving energy cost savings. The total annual savings that can be attributed to operational energy management from these cases is in excess of R41 million. This illustrates how effective operational energy management can be in specific cases. In the next section, operational energy management will be evaluated more generally, specifically where small improvements are found that are not easy to attribute to a single action.

5.4 Evaluation of group results

Three methods are proposed for the validation of the impact of the methodology on the whole of GM Group 1. The first method evaluates whether there has been an improvement in the TOU performance throughout the group, meaning that energy use has decreased during expensive peak period and increased during inexpensive off-peak periods. The second method evaluates whether the total number of occurrences of systems consuming an unusually high quantity of electricity has decreased throughout the group. Finally, the group's energy intensity will be evaluated as a whole.

5.4.1 Cost saving through improved control

The first, and easiest to evaluate, would be to compare the group's performance regarding TOU tariffs for the two years. An improvement in TOU performance, such as a reduced demand for electricity during peak periods, would be indicative of an improvement in electricity demand management. An example of this is shown in Figure 99. In this figure, electricity consumed during peak periods has been shifted to rather be consumed during an off-peak period. Although the total electricity consumption may remain the same, there is a resulting cost saving.

To calculate the savings that would result by reducing peak and standard time electricity consumption and increasing off-peak electricity consumption, a year-on-year analysis was performed. This analysis was done by using data for total electricity consumed throughout different periods and determining what percentage of total electricity was consumed during which cost period. The electricity consumption distribution can then be compared with the baseline year, thereby performing a 'what-if' analysis.

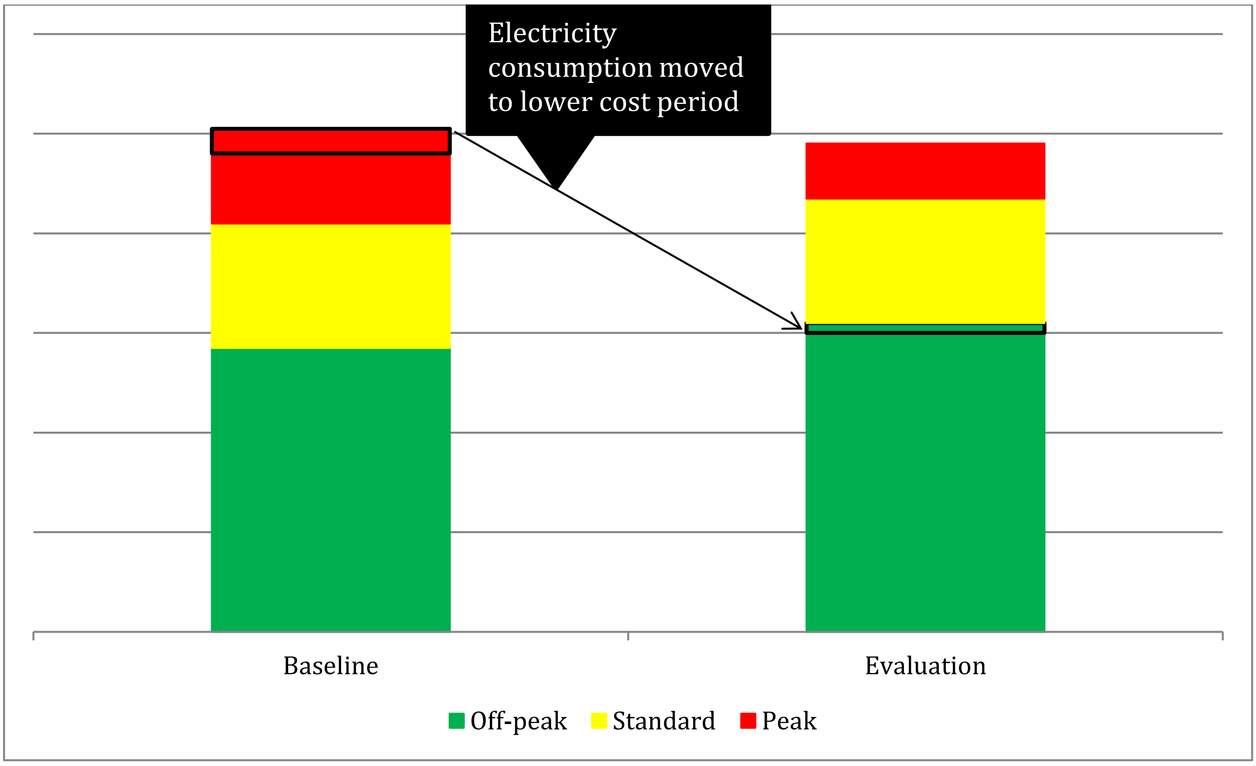

Figure 99: Improved TOU performance

An important factor that played a role in the analysis was the introduction of changed winter peak periods for 2015. As this change came in the performance year, it made it impossible to do a full year-on-year analysis. This is because the Eskom peak period was moved an hour earlier. This would lead to a change in performance even if no intervention took place, as many mine functions cannot be moved to accommodate the change. As a result, only low season energy consumption trends were compared.

To perform this analysis, verified data from Eskom invoices was used to ensure the most accurate data source was used. By performing the analyses as discussed, the following results were obtained. There was an overall nett shift of electricity demand to reduce costs. This resulted in an annual cost saving of R2.5 million at 2016/17 tariffs. If winter periods could be included, this might have resulted in a total saving of close to R5 million.

5.4.2 Energy efficiency through improved control

The second effect would be a reduction in the number of high demand outliers in energy performance. If the number of outliers greater than average consumption decrease year-on-year, this is indicative of improved performance, as instances of systems consuming more electricity than planned will have been reduced. An example of this is shown in Figure 100, where improved control has reduced the number of outliers lying to the right of the graph.

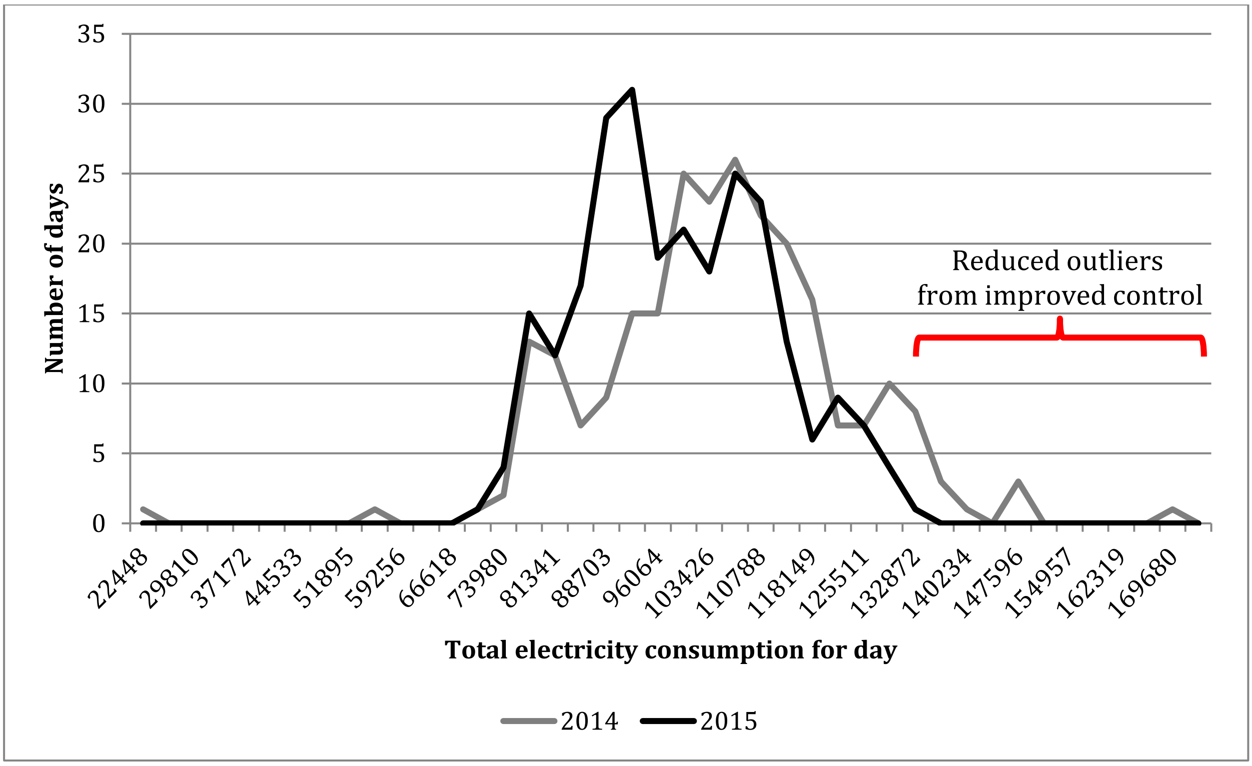

Figure 100: Example of improved control and reduction in outliers for Site 1's compressed air system

Statistical analysis can be used for effective evaluation. To conduct the analysis, mining, hostel and surface systems were chosen to represent a control group. This is because these users are typically not linked to a single control room, and far less likely to see an improvement due to operational energy management.

For the analysis, the data for the different systems was evaluated to decide whether to include or exclude the system. The primary criteria for exclusion was a significant period (≥ 1 month) of non-standard operation or data loss.

Table 34: List of sites and systems excluded from statistical analysis

Site	System	Reason
Site 2	All	Non-production status for six months
Site 4	All	Data reliability
Site 5, Shaft 1	Compressors	Offline for six months
Site 6, Shaft 2	All	Data loss
Site 7, Shaft 2	All	Non-production status throughout evaluation period

After the elimination process, 40 systems remained to be analysed. Of this, 10 were part of the control group and 30 part of the test group. The resulting data set was analysed statistically to determine whether a significant impact showed when comparing the test group with the control group.

The quantity of electricity consumed above average decreased for 14 out of 30 evaluated systems, compared with 1 of 10 control systems. The confidence of the savings not occurring by random chance is greater than 99.9%. There is an extremely high confidence that the effect seen on the test systems is not simply a random occurrence, but rather the result of an intervention. This reduced unnecessary excess consumption and saved approximately 16.1 GWh throughout the group for the evaluation year. The resulting cost savings is approximately R11.3 million at 2016/17 tariffs.

Table 35 shows a breakdown of the reduction achieved in outliers, categorised by system. The three control system types are shown in grey. There was a significant difference in change between the control systems and the systems where improvement was expected. While only one control system showed an improvement, nearly half of the evaluation systems showed an improvement.

An important trend that was found was that systems that had already been optimised as part of Eskom-funded DSM projects did not improve as much as other systems. The compressor system was the most prominent example of this. A small number of pumping systems also improved, which is also a system that is often targeted for DSM projects.

Table 35: Breakdown of reduction in outliers by system

	Reduction in outliers	Percentage of systems improved
Mining	−15%	0%
Surface	−16%	0%
Hostels	1%	50%
Fans	28%	60%
Hoisting	34%	38%
Pumping	37%	25%
Refrigeration	41%	50%
Compressors	3%	40%
Plant	18%	100%
Control	−8%	17%
Actual	24%	43%

Table 36 shows a breakdown of the improvements achieved categorised by site. A trend that becomes clear from this analysis is that most sites had an average level of performance. Two sites showed little buy-in to the process, and showed very little to no improvement. One site performed far better than average.

Table 36: Breakdown of reduction in outliers by site

	Reduction in outliers	Percentage of systems improved	Cost saving
Site 1	21%	83%	R3 765 717
Site 3	−6%	40%	− R84 092
Site 5	2%	11%	R1 982 656
Site 6	−6%	0%	−R341 067
Site 7	3%	40%	R819 821
Site 8	4%	50%	R2 026 815
Site 9	11%	33%	R 2 033 136

5.4.3 Improvement in overall group energy intensity

The final method of evaluating the effectiveness of the methodology evaluates the improvement of performance of the group as a whole with regards to energy intensity. Annual electricity consumption was compared to the total production of the mine shafts, with a decrease in overall energy intensity expected.

Table 37 shows a summary of the overall change in group energy intensity. As is reflected in the results from Section 5.4.2, Site 3 and Site 6 did not show an overall improvement when the methodology was applied. Several factors could play a role in this, including a lack of buy-in from the operation's side, as well as changing operating conditions between the baseline and assessment periods.

Including all sites in the calculation shows an overall improvement throughout the group of 2.39%. However, when excluding Site 3 and Site 6, an improvement of 4.69% is shown throughout the rest of the group. However, site specific savings range from 2.28% to 9.89%. This is within range of the potential 5% savings identified in literature.

Table 37: Summary of change in group energy intensity

	Intensity (kWh/tonne milled)		Improvement: 2015 vs 2014
	2014	2015	
Site 1	593	571	3.67%
Site 3	139	161	-15.82%
Site 5	435	426	2.00%
Site 6	271	283	-4.60%
Site 7	298	269	9.89%
Site 8	333	309	7.30%
Site 9	271	265	2.28%
All sites	**2 339**	**2 283**	**2.39%**
Improved sites	**1 930**	**1 839**	**4.69%**

These savings prove that an approximate 33.7 GWh of electricity was saved throughout the group on sites where uptake of the methodology was high. The equivalent cost saving is R25.3 million.

5.5 Conclusion

In this chapter, a case study was presented where an integrated approach to operational energy management was applied to one of South Africa’s largest gold mining groups. First, the metering available on the mine was evaluated to verify the meters where possible, and to identify areas for attention. Secondly, a data management structure was put in place, ensuring that data errors were managed proactively. Thirdly, a new budgeting methodology was developed and implemented. This methodology was shown to be more accurate than the model employed by the mine in 100% of cases. Finally, a feedback strategy was developed and implemented.

The impact of operational energy management was shown in several specific cases. Operational energy management was shown to have identified non-conforming systems, determining the financial impact and alerting the relevant personnel in several cases. In total, an annual cost saving of R41.9 million was shown to be attributable to operational energy management in specific instances.

The years 2014 (baseline) and 2015 (evaluation) were analysed to determine the impact of the strategy. The results show that savings of at least R25.3 million were achieved due to improved control of the mine systems. An additional R2.5 million savings were realised through optimisation of operations for TOU tariff periods.

Chapter 6 Conclusions and recommendations

6.1 Overview of study

There is significant pressure on South African industry to improve energy efficiency. This is driven by a global drive to improve energy efficiency in industry, legislation enacted or soon to be enacted by government, and substantial increases in energy prices. These changes have caught the industrial sector in South Africa unprepared. Long periods of low energy costs mean that good energy practices have not had time to develop. Further, the sluggish global economy means that industry has very little capital to spare for technology-replacement energy efficiency projects.

Although support is provided to industry in the form of standards such as ISO 50001, these standards were developed as generic guidelines and do not provide sufficient technical assistance. Energy managers are therefore required to rely on their own technical knowledge to improve energy performance. This problem is exacerbated by the small number of staff appointed in South African industry to focus solely on energy performance.

Operational energy management has been identified as a potential solution. Operational energy management consists of accurate measurement, evaluation of performance, and feedback regarding performance to motivate improved energy performance. Energy savings of 5% at very low capital cost have been reported in literature. However, there are several hurdles to implementing operational energy management. This type of energy management relies on effective energy measurement, analysis and feedback. No literature could be found that provides a method to implement one or all these steps comprehensively.

In this study, a strategy for operational energy management in South Africa was developed. A comprehensive review of literature and practices already existing in industry was conducted. Literature related to measurement, analysis and feedback was reviewed and analysed. From this, as well as investigation of industry, a list of requirements was developed for an operational energy management strategy to be effective.

Based on these requirements, a methodology was developed. The methodology provided a systematic process for identifying energy metering locations. A strategy for ensuring data validity was also provided, which ensured that the resulting data was accurate enough to be effective.

Finally, a strategy was developed for ensuring energy data integrity and managing energy data is developed.

In the next section, a methodology was developed for analysing energy data. This methodology began with a systematic process for developing an energy driver network. This network ensured that the user could comprehensively identify all energy drivers acting on the various systems. Once this network was developed, a process was provided for collecting relevant information and data for each system. From this, every system could be characterised, resulting in an accurate energy performance model. For situations where this model could not be developed or utilised effectively, a novel method for developing a historical and metadata model was provided.

Finally, a methodology for providing effective energy feedback was developed. This methodology again started by following a systematic process to identify all relevant stakeholders who required energy feedback. Following this, a comprehensive process for developing feedback for each individual recipient was provided. This step is critical as it ensures that operational personnel are empowered to manager operational efficiency. Operational energy management was therefore decentralised, assisting the small number of energy managers currently active in South African industry.

The result of this process was a new comprehensive methodology for effective operational energy management. The methodology was validated through implementation in the South African gold mining sector, on one of South Africa’s largest gold mining groups. The case study showed the implementation of the methodology throughout the group, with consideration given for effectively using the information and systems already in place, and supplementing them to ensure compliance with operational energy management.

Through this implementation, the new historical and metadata method for determining energy performance was implemented by using the method to develop new operational budgets for the group’s various systems. This method was shown to be effective compared with the method already used by the mine. The existing method had an error of 16.5% compared with actual, whilst the improved method reduced the error to less than 2%. Further, the improved method showed an improvement on every system to which it was applied. The new method for determining energy performance was therefore validated.

Several cases of improvements on individual systems were reported. By ensuring that poor energy performance was quickly identified and acted upon, a significant cost savings was achieved. R41.9 million of annual energy cost savings can be attributed to operational energy management.

Throughout GM Group 1, the group's performance regarding Eskom TOU periods was evaluated. The group showed an overall improvement during summer periods, with the overall cost of electricity being reduced by increasing usage in cheaper periods and reducing usage in expensive peak periods. The total cost saving was shown to be approximately R2.5 million. The winter period savings could not be evaluated, due to changes in Eskom high demand season peak billing schedules.

Further, the effectiveness of the methodology causing improvements in operational performance by reducing non-conformities and outliers was evaluated. Systems that were not expected to show significant improvement from operational energy management were used as controls, and the improvement in the remaining systems was statistically evaluated against them. The results showed with greater than 99.9% confidence that operational energy management did have an effect. The savings was shown to be approximately R11 million per annum.

This reduction in unnecessarily high usage contributed to the overall improvement in performance of GM Group 1. Through a simple intensity analysis, it was shown that a 3.53% improvement was achieved with regard to operational intensity. In cost value, this is the equivalent of a R25.3 million cost saving that can be attributed to operational energy management.

Overall, the purpose of operational energy management was to improve energy performance. This could be viewed as by reducing energy costs and causing energy savings. As the case studies showed, these cost savings were achieved, thereby validating the new strategy for dynamic operational energy management in South African industry.

6.2 Contributions

Principal contribution

A new system-based strategy for integrated operational energy management

The primary contribution of this study was to provide a complete strategy for achieving operational energy management. This contribution is made unique as no other literature was found that provided a comprehensive method for implementing operational energy management. Further, the contribution is also unique due to the system-based approach that was used, which has not previously been used for operational energy management. This methodology was validated by achieving more than R50 million in energy cost savings in specific and general applications in South African industry.

Component contributions

A unique system-based energy measurement and energy data management procedure for South African industry

This study presented a methodology for energy measurement and data management as part of operational energy management. This contribution is made unique due to no previous work providing for measurement locations, quality as well as data integrity and management. This methodology was validated by applying it to a South African gold mining group and accurately validating energy measurements for further use as part of operational energy management.

A novel energy performance analysis strategy for industry

A novel strategy for effective energy performance analysis was developed. This contribution is made unique due to no other literature providing a systematic method for evaluating energy drivers between systems. Further, a unique method was developed using historical and metadata that allows for an accurate model of energy performance to be developed. This contribution was validated by implementing it on a South African gold mining group. The methodology provided energy budgets that significantly improved on existing budgets in terms of accuracy.

A novel strategy for sustainable operational energy management through integration and effective feedback

In this study, a novel strategy for achieving operational energy management through feedback was developed. This contribution is made unique due to no previous work showing a methodology for identifying stakeholders and how to develop individual feedback for each stakeholder. The proposed methodology is also unique due to ensuring that operational energy management can be sustained by integrating feedback into operational procedures. This was validated using feedback to identify several specific non-conformities resulting in energy cost savings of nearly R40 million.

6.3 Limitations and further work

Several areas where further research is required were identified during this study. The foremost of these is the need for an energy information management system that is specifically suited to address the needs identified in this study. These include data integrity and distribution management, timely analysis of energy data to determine energy performance, and providing automated feedback capabilities.

With specific regard to energy measurement, the South African environment is continually changing. Due to new legislation that has been proposed and is waiting to be implemented, further work may be required to ensure that energy measurement meets these requirements. Although not specifically pertinent to operational energy management, this will become a key concern for energy managers, especially if a carbon tax is introduced as expected.

In terms of energy data analysis, further work is required to improve the effectiveness of energy models even more. It is proposed that a methodology that uses simulations to model energy performance be researched. Such a methodology may further improve the accuracy of energy performance models.

Operational energy management was gradually implemented throughout GM Group 1 from July 2013 through 2015. Following this, an ISO 50001-compliant energy management system was implemented in one shaft of the group, with the other shafts set to follow. The impact of operational energy management as a precursor to formal energy management should also be investigated. It is possible that this first step provides several benefits, such as making personnel energy aware, and proving energy savings before a more comprehensive investment into energy management is made.

One area of concern was the remainder of barriers to the uptake of energy management. This was shown by the fact that two sites in the case study group showed no improvement. Although this study addressed the barriers of a lack of an access to capital and a lack of specialised knowledge, it could clearly not overcome the additional barriers present on these sites. Barriers to energy efficiency have been studied in developed countries, but no studies specific to South Africa were found in literature. It therefor represents a research area that needs to be explored to assist South African industry further with improvements in energy efficiency.

This study has shown the implementation of the strategy in the gold mining industry. At time of writing, certain components of operational energy management had been applied in the cement and steel industries. Further implementation in the steel industry is currently planned. The effectiveness of operational energy management in this industry should also be evaluated to determine its applicability in other environments.

This study presented a comprehensive literature review of concepts applied in operational energy management. However, research in this important field is ongoing. No state-of-the-art review could be found in available literature. Such a review would be useful in providing guidance for improvements to the operational energy management strategy provided.

Further work is required regarding the potential for applying the methodology in areas other than operational energy management, or energy management at all. As the methodology follows a systematic process, and is intended to improve ongoing processes, there are several areas within which it may be useful. Two particular areas may be quality management systems, where ISO 9001 is applicable, environmental management systems (ISO 14001) and health and safety management systems.

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Appendix A

GM 1 Group logo

Electricity consumption report

Site 1

GM Group 1 report graphic

18 May 2014 - 6 Jun 2014

1 Summary

Table 1-1: Power consumption summary

Component	Month to date					
	Actual (kWh)	Budget (kWh)	Actual cost		Over/under(-) budget	
Site 1	**6 535 436**	**8 491 562**	**R**	**3 941 162**	**R**	**-1 295 423**
-Compressors	1 614 822	2 240 750	R	1 004 407	R	-377 422
-Fans	898 340	915 575	R	552 451	R	-12 167
-Hoisting	637 022	650 397	R	398 520	R	-2 568
-Hostel	885 750	720 000	R	548 091	R	104 081
-Mining	917 686	720 000	R	545 749	R	101 739
-Pumping	4 460	648 720	R	2 567	R	-397 486
-Refrigeration	1 302 895	1 468 800	R	707 687	R	-198 094
-Processing	58 227	28 000	R	44 231	R	26 964
-Surface	109 197	134 400	R	68 643	R	-14 239

2 Section summaries

2. Site 1 total

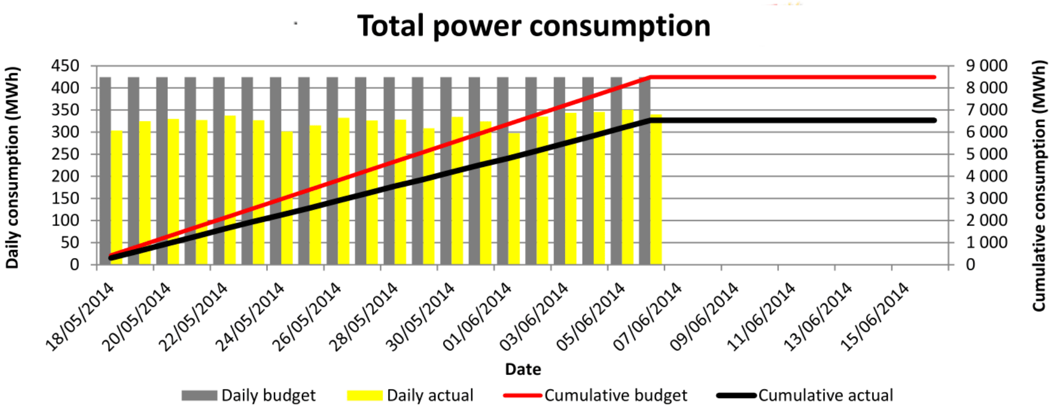


Figure 2-1: Total and daily power consumption

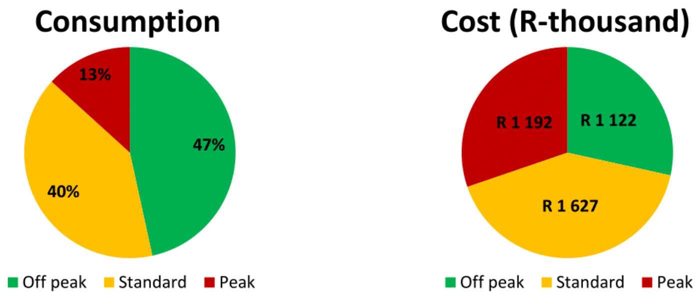


Figure 2-2: TOU performance

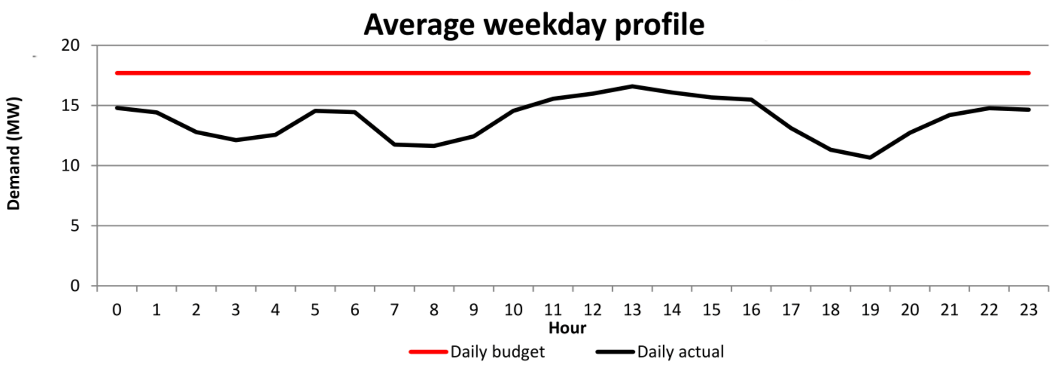
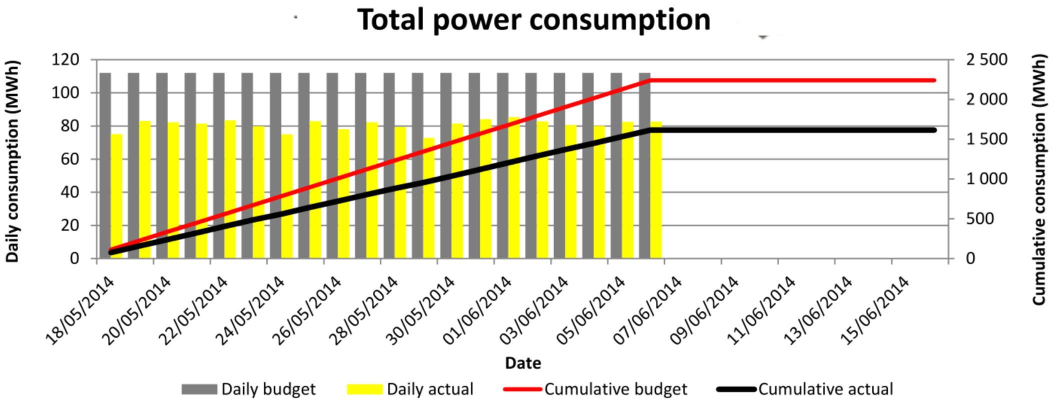


Figure 2-3: Average weekday profile

2.2 Compressors



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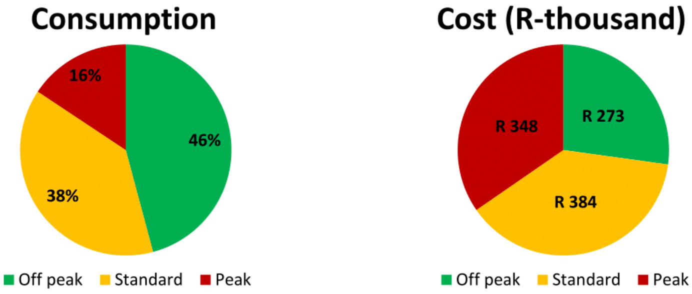

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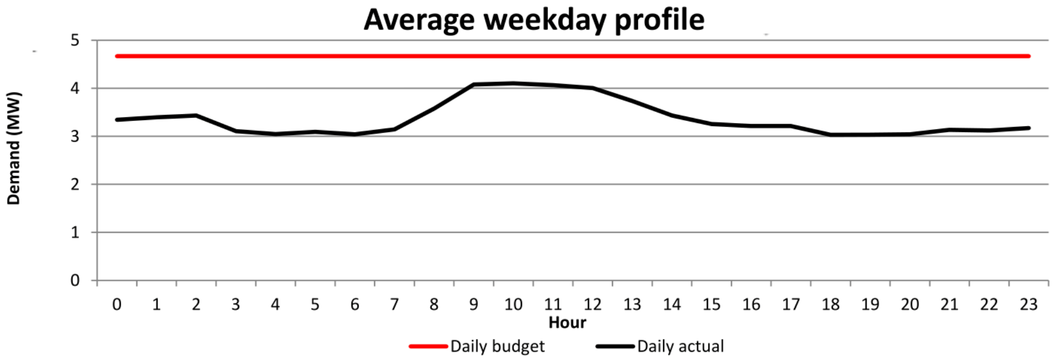


Figure 2-6: Average weekday profile

2.3 Fans

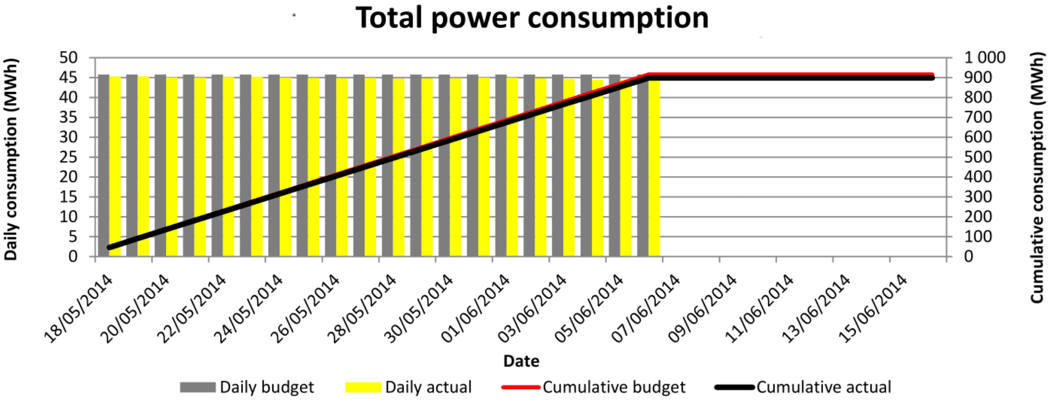


Figure 2-7: Total and daily power consumption

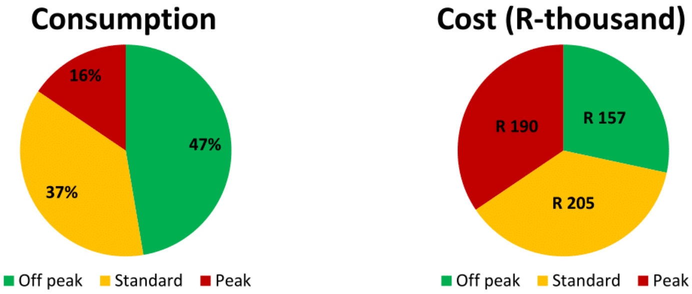


Figure 2-8: TOU performance

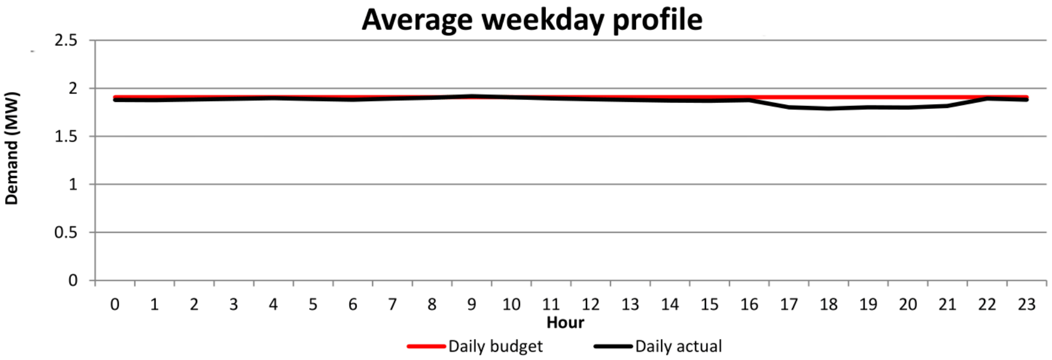


Figure 2-9: Average weekday profile

2.4 Hoisting

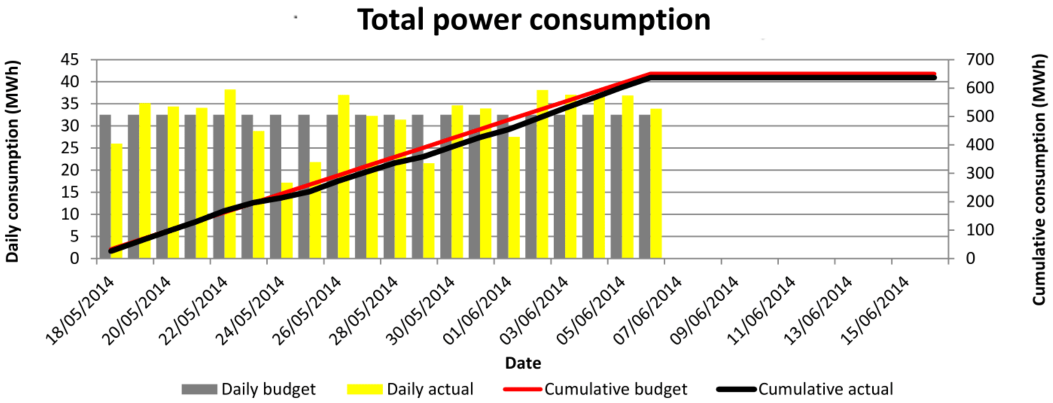


Figure 2-10: Total and daily power consumption

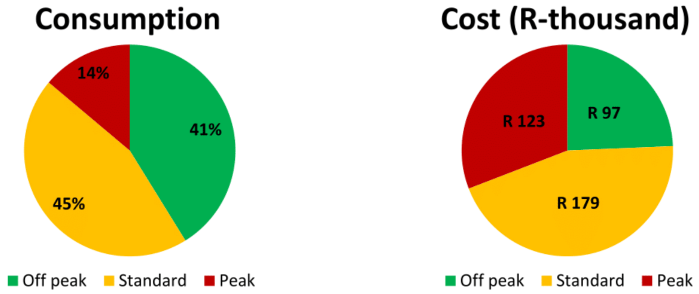


Figure 2-11: TOU performance

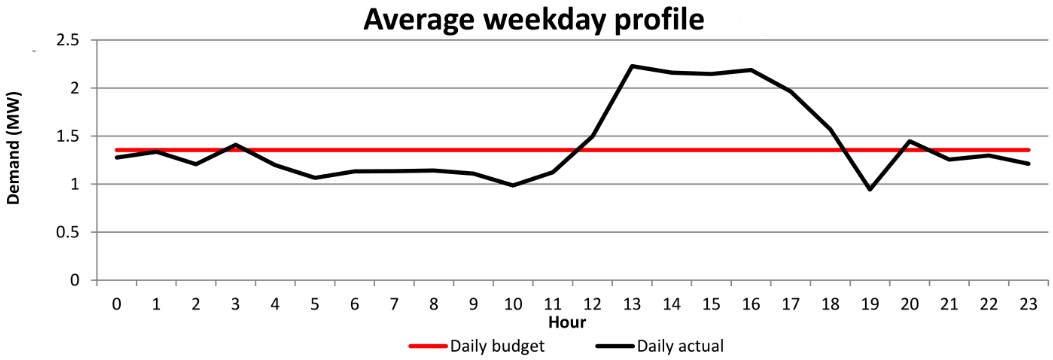


Figure 2-12: Average weekday profile

2.5 Hostel

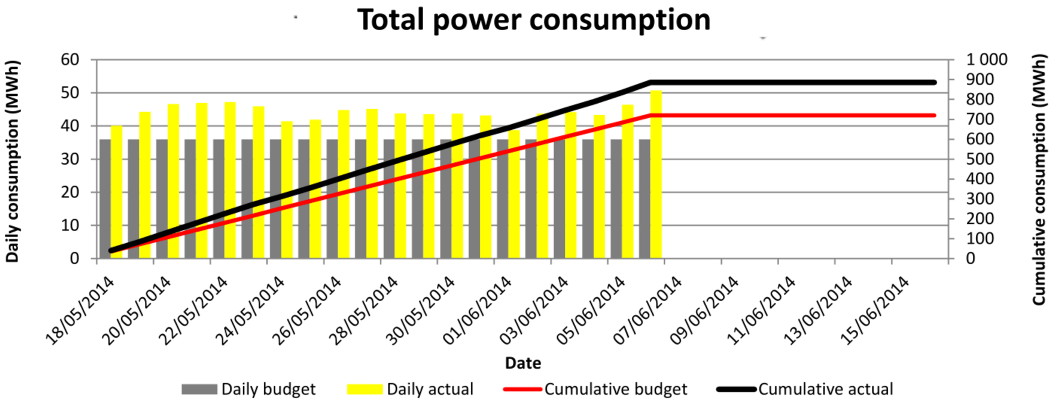
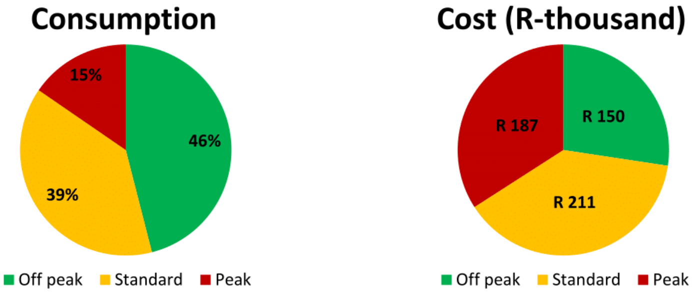


Figure 2-13: Total and daily power consumption



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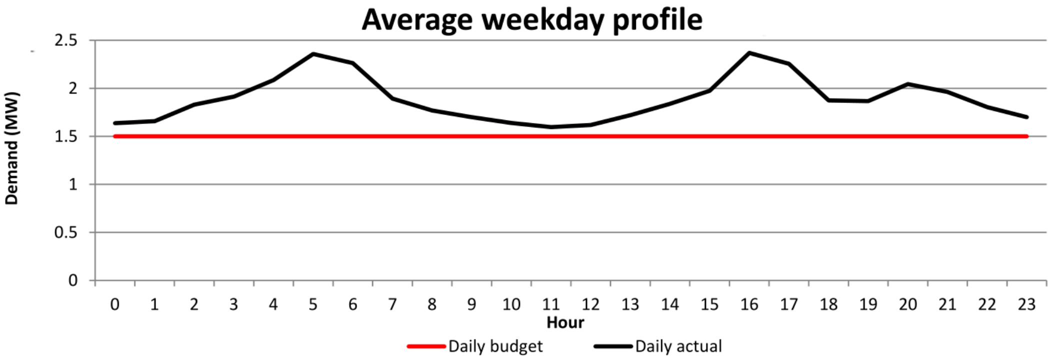

Figure 2-15: Average weekday profile

2.6 Mining

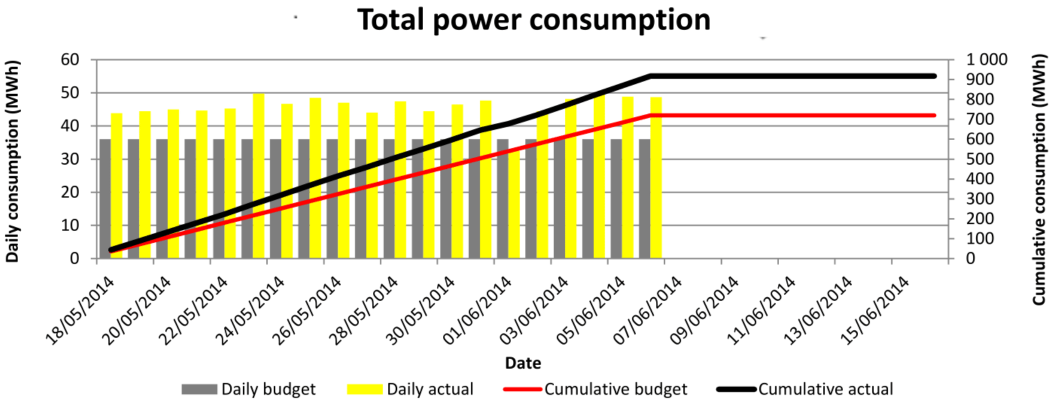

Figure 2-16: Total and daily power consumption

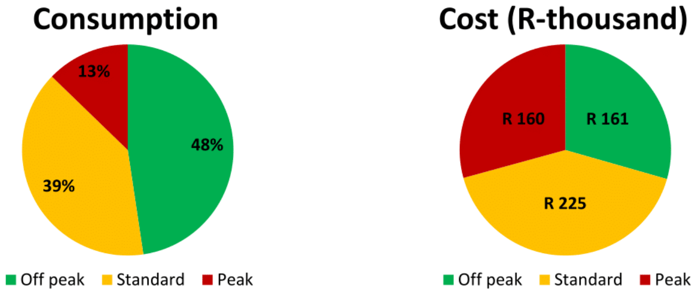

Figure 2-17: TOU performance

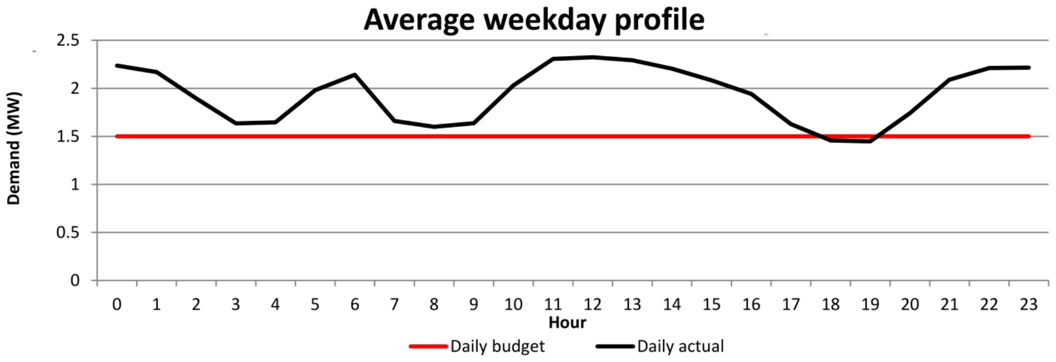

Figure 2-18: Average weekday profile

2.7 Pumping

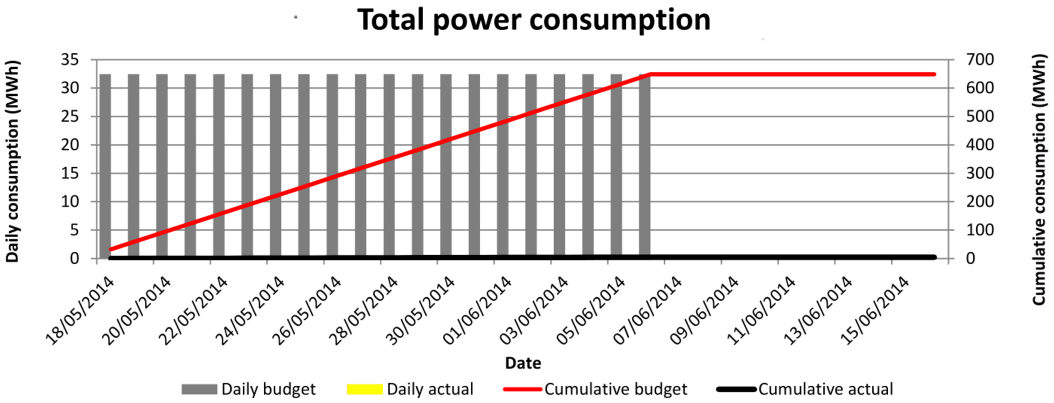

Figure 2-19: Total and daily power consumption

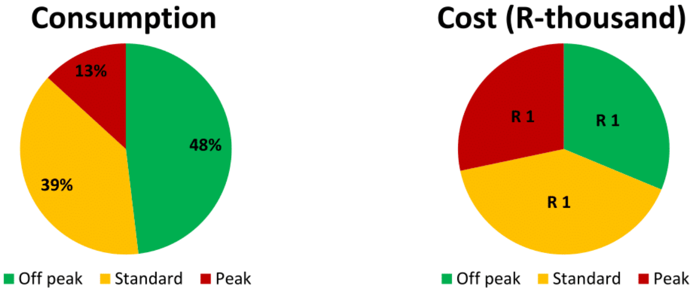

Figure 2-20: TOU performance

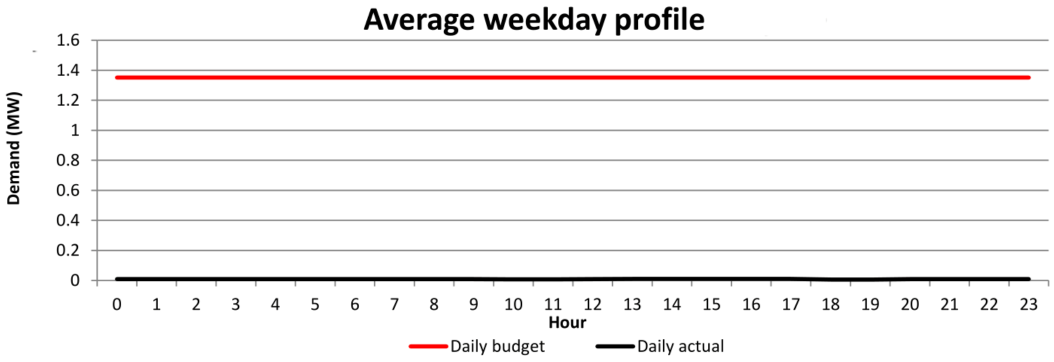

Figure 2-21: Average weekday profile

2.8 Refrigeration

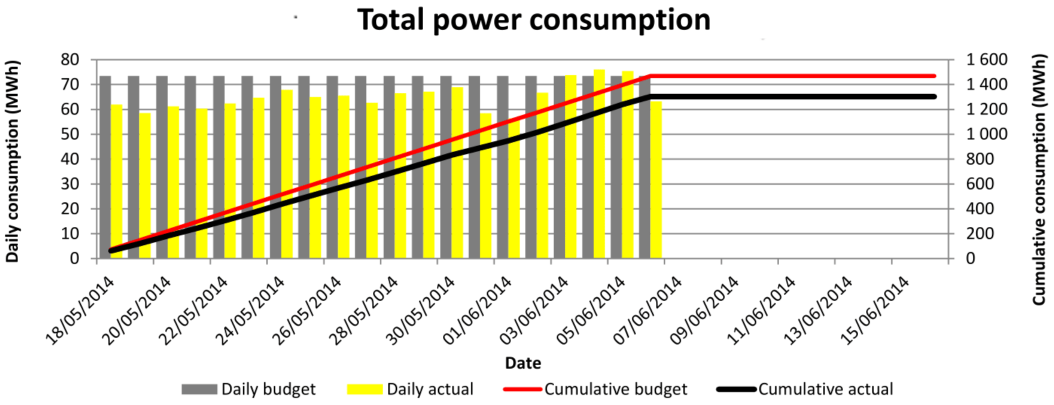

Figure 2-22: Total and daily power consumption

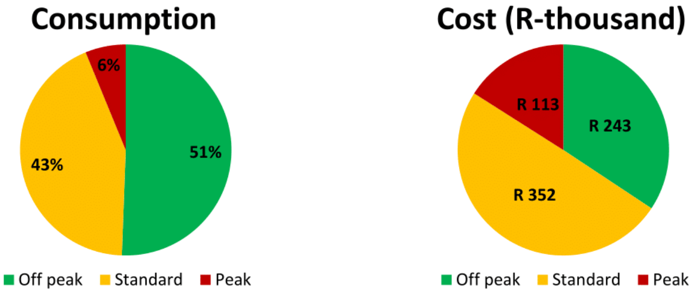

Figure 2-23: TOU performance

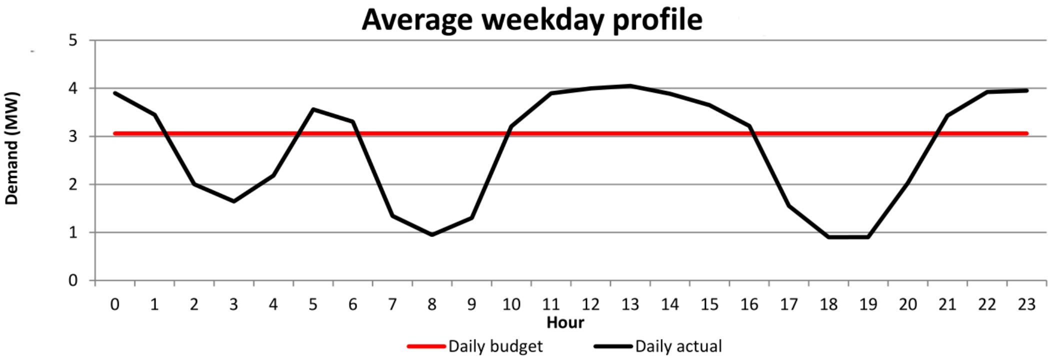

Figure 2-24: Average weekday profile

2. Processing

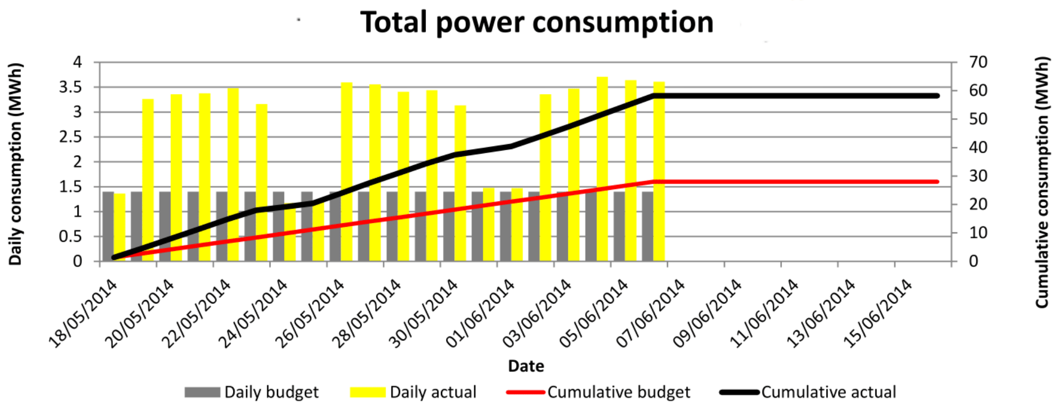

Figure 2-25: Total and daily power consumption

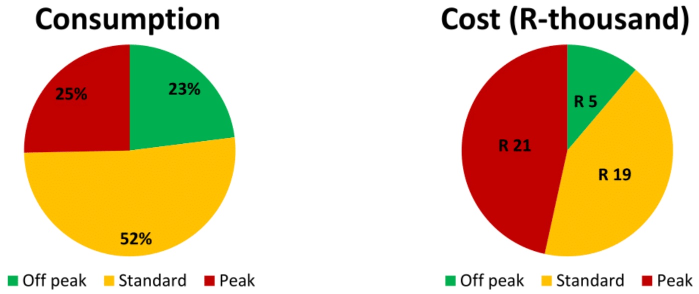

Figure 2-26: TOU performance

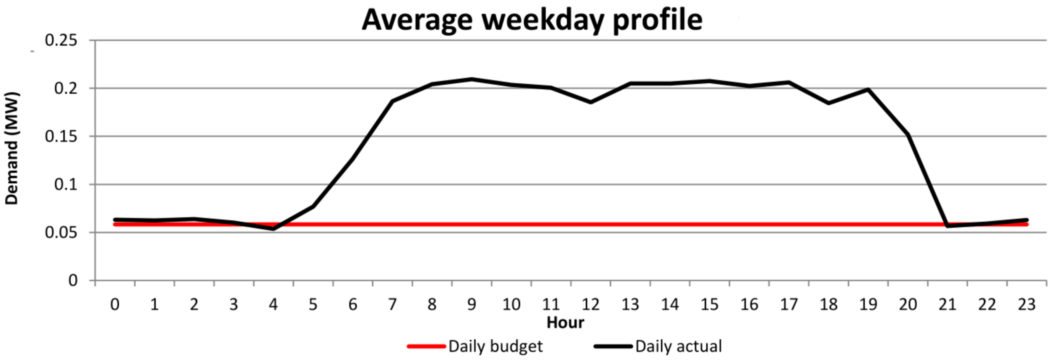

Figure 2-27: Average weekday profile

2.10 Surface

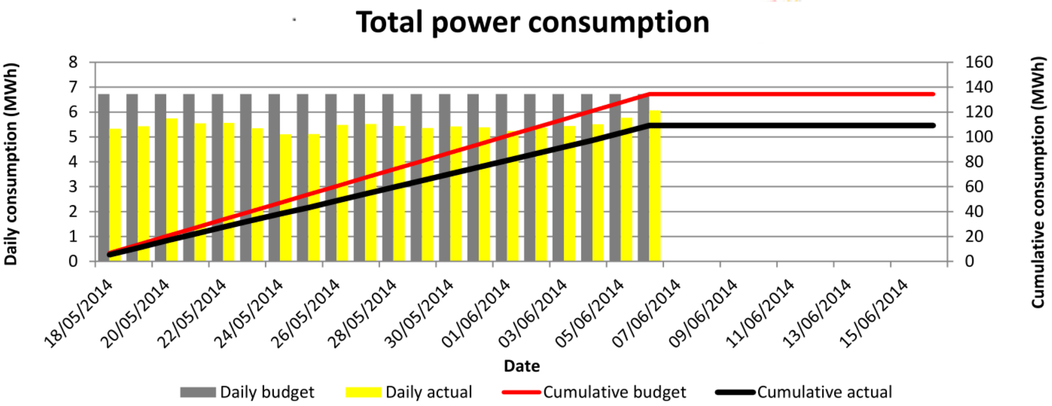

Figure 2-28: Total and daily power consumption

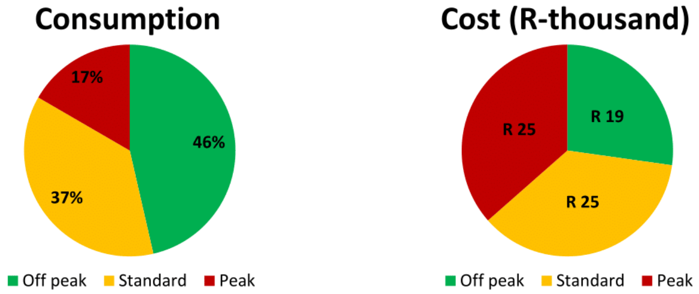

Figure 2-29: TOU performance

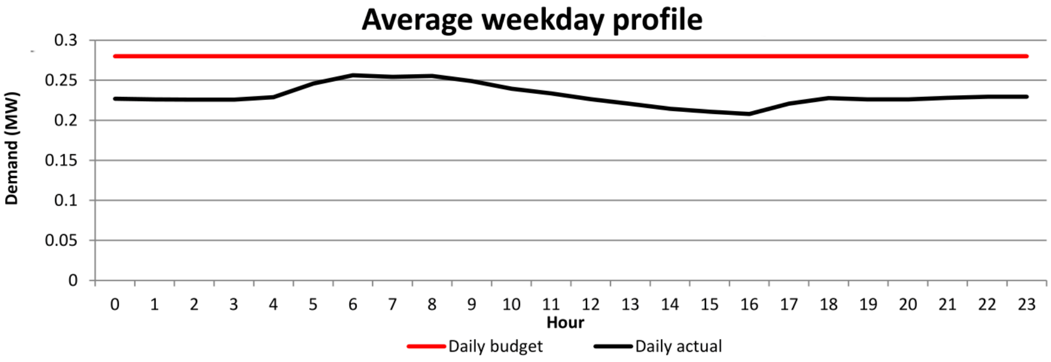

Figure 2-30: Average weekday profile

Appendix B

1 Daily Performance

Table 1-1: System overview (30 April 2015)

System	Budget (kWh)	Actual (kWh)	Variance	Processes over budget	Processes under budget
Site A	2 143 246	1 606 893	-25.0%	Refrigeration 6%,	Fans 25%, Pumping 42%, Compressed Air 23%, Mining load 24%
Site B	1 458 024	1 486 002	1.9%	Mining 19%, Winders 6%, Refrigeration 3%,	Pumping 16%, Fans 37%, Compressed air 11%
Site C	319 523	316 333	-1.0%	Pumping 31%, Refrigeration 24%, Compressed air 88%	Mining 49%, Fans 22%,
Site D	615 372	478 193	-22.3%	Fans 29%,	Compressed air 52%, Mining 10%, %, Refrigeration 76%
Site E	1 129 073	1 162 860	3.0%	Fans 24%, Mining 18%,	Refrigeration 2%, Pumping 38%, Compressed air 14%
Site F	781 854	593 312	-24.1%		Fans 15%, Mining 11%, Pumping 55%, Refrigeration 22%, Compressed air 18%
Site G	1 747 399	1 295 955	-25.8%		
Site H	228 294	161 556	-29.2%		
Total	**8 422 785**	**7 101 103**	**-15.7%**		

2 Monthly Performance

Table 1-2: System overview (01 to 30 April 2015)

System	Budget (kWh)	Actual (kWh)	Variance	Processes over budget	Processes under budget
Site A	20 756 815	14 854 720	-28.4%		Fans 23%, Pumping 40%, Refrigeration 8%, Compressed Air 31%, Surface 2%, Mining 26%
Site B	14 369 405	14 063 613	-2.1%	Mining 17%, Winders 5%,	Refrigeration 1%, Pumping 20%, Fans 47%, Compressed air 14%
Site C	3 224 755	3 011 468	-6.6%	Pumping 58%, Refrigeration 97%, Compressed air 88%	Mining 50%, Fans 31%,
Site D	5 859 035	4 958 165	-15.4%	Fans 33%, 10%,	Compressed air 42%, Mining 9%, Refrigeration 75%
Site E	11 318 080	11 467 372	1.3%	Fans 7%, Mining 17%,	Refrigeration 5%, Pumping 36%, Compressed air 4%
Site F	7 404 023	6 078 221	-17.9%		Fans 7%, Mining 3%, Pumping 56%, Refrigeration 10%, Compressed air 15%
Site G	17 263 740	13 765 415	-20.3%		
Site H	2 256 169	2 222 220	-1.5%		
Total	**82 452 022**	**70 421 195**	**-14.6%**		