COST IMPLICATIONS OF MODERN MINING METHODS ON WATER AND ENERGY CONSUMPTION: A SOUTH AFRICAN PLATINUM CASE STUDY

Fatheela Brovko

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Masters of Science in Engineering.

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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This 18 day of March 2021

ABSTRACT

South Africa has an exceptional mineral wealth that enabled its industrial and economic development in the 19th and 20th centuries; and that continues to play a major role in its future development goals. South Africa has the largest platinum reserves in the world, and its platinum mining sector is a major contributor to its mineral exports. However, the country's platinum industry however, faces many challenges that threaten its growth and sustainability, two of which are access to water and energy.

Water and energy are critical inputs to platinum mining and a continuous uninterrupted supply of these resources is required. South Africa however, faces increasing water and energy risks in the forms of continued droughts, electricity supply shortfalls, above-inflation electricity price increases and competition for electricity and water resources from other industries, governments and communities. To ensure its growth and sustainability, the platinum mining industry is transitioning from conventional mining to more modern mining methods that include improved technologies and processes in conventional mines, mechanisation and continuous mining operations. This study aimed to determine the consumption and cost implications with respect to energy and water associated with the implementation of modernisation in the narrow reef platinum mining industry.

A platinum case study was undertaken, using information from published literature and where possible actual mine data between 2013 and 2017 to determine whether modernised conventional mining and the implementation of mechanisation will improve water and energy efficiencies. The study found that that mechanised mining were 47% more energy efficiency and 87% more water efficient (for potable water) compared to conventional operations, that resulting in significant cost savings. Furthermore, the study forecasted total energy and water demands up to 2043 that illustrated that the modernisation of the platinum industry will result in significant consumption and cost savings from energy and water perspective.

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LIST OF ACRONYMS

Carbon Disclosure Project	CDP
Electricity Supply Commission (South Africa)	ESKOM
Gross domestic product	GDP
Greenhouse gas	GHG
Global International Water Assessment	GIWA
Global Reporting Initiative	GRI
Global Water Initiatives	GWI
Global Water Partnership	GWP
Internet of Things	IOT
Iron and Steel Corporation (South Africa)	ISCOR
Load-Haul-Dump	LHD
Low profile	LP
Platinum Group of Metals	PGM
South African Synthetic Oil Limited	SASOL
Upper Group 2 (Bushveld Complex)	UG2
Ultra-low profile	ULP
United Nations	UN
United Nations Water	UN-Water
Water Accounting Framework	WAF
Water Footprint Network	WFW
World Water Assessment Programme	WWAP
World Water Council	WWC
Extra-low profile	XLP

LIST OF SYMBOLS AND UNITS

Carbon dioxide	CO_2
Gigajoule (10^9 Joules)	GJ
Gigawatt-hour(s)	GWh
Hours	hrs
Kilogram	kg
Kilolitre (one thousand liters)	kl
Kilowatt	kW
Kilowatt-hour(s)	kWh
Litres per second	l/s
Meter	m
Cubic meter	m^3
Millijoule (10^6 Joules)	MJ
Millimeter	mm
Ounce	oz
Palladium	Pd
Platinum	Pt
South African Rand	R
Tonne (1000 kilograms)	t
TeraWatt hour(s)	TWh
United States dollar US$	

1 INTRODUCTION AND BACKGROUND

1.1 Background to the Study

1.1.1 Mining in South Africa

The geographic location and geological nature of ore deposits are constrained by geological processes that occurred several million years ago, independent of current political and country boundaries, thus resulting in resource-abundant and resource-dependent countries (Küblböck, 2013). From these geological processes, South Africa is a country with exceptional mineral wealth of many kinds. It hosts 87% of the world's platinum group metals in its unique Bushveld Complex, 29% of the world's known gold reserves (mostly within the Witwatersrand Basin), 80% of the world's manganese and 72% of the world's chromium (Minerals Council South Africa, 2018). Additionally, there are other commodities that South Africa hosts that are not a large percentage of the world's deposits, but are important for exports and local use, such as aluminosilicate minerals, ferrochromium, vanadium, diamonds, coal, iron ore, zinc, nickel and industrial minerals (Rossouw and Baxter, 2011; Minerals Council South Africa, 2018).

Since the discovery of diamonds in Kimberley over 150 years ago and the subsequent discovery of the Witwatersrand gold fields in 1886, the South African mining industry played a critical role in transforming the country from an agricultural economy to an industrialised nation (Kane-Berman, 2017). The mining of diamonds and gold quickly expanded to other commodities, such as coal and platinum and led to the rapid development of rail networks, key transportation hubs as well as the establishment of factories and universities (Kane-Berman, 2017). ESKOM, ISCOR, SASOL and the Rand Water Board were founded to support the needs of the mining industry and major towns were built around the mining activities such as, but not limited to Johannesburg and Kimberly (Kane-Berman, 2017).

The contribution of mining to South Africa's economy has dwindled from 21% in

1980 to 7% in 2018 as illustrated in Figure 1.1 (Monteiro and Njini, 2018). Kane-Berman (2017) mostly attributes this decline in the mining industry to the growth and expansion of other sectors (such as government and finance) as the South African economy matured, but acknowledges that other factors such as slumps in commodity prices, regulatory uncertainty and labour disputes may also have contributed. Despite the decline, in 2017 the mining industry accounted for 7.5% of overall Gross domestic product (GDP) of South Africa in real terms, contributing R335 billion through direct contributions to fixed investment, royalties and taxes (Minerals Council South Africa, 2018). Mining is responsible for approximately 27% of South Africa's exports (Minerals Council South Africa, 2018), including precious and industrial metals. The mining industry accounts for 25% of foreign direct investment as well as 11% of gross fixed capital formation (Kane-Berman, 2017). The mining industry also represents a large market for domestic suppliers of goods and services (Kane-Berman, 2017).

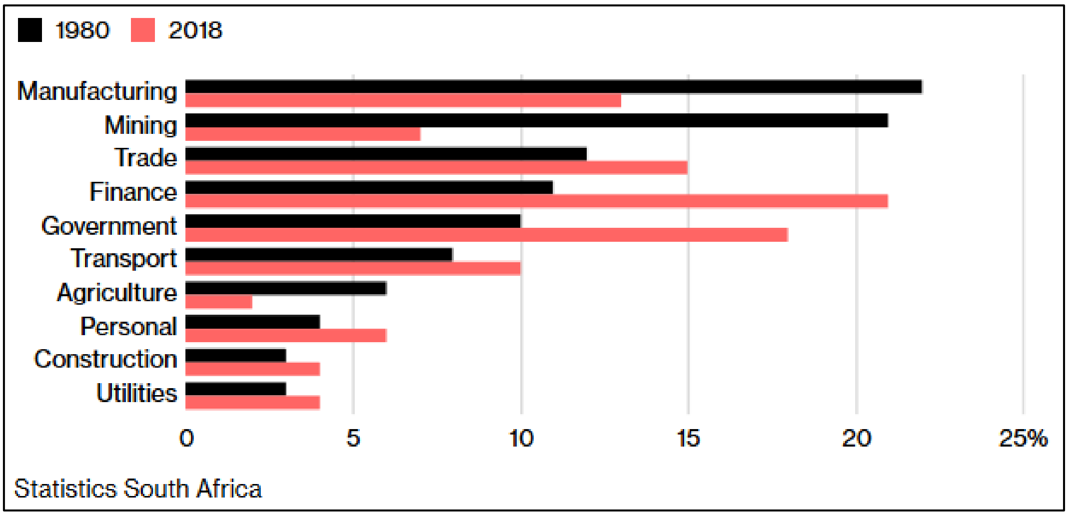

Figure 1.1 Sectoral contribution to South Africa's GDP (in percentage) in 1980 and 2018 showing the changes in relative GDP contribution (Monteiro and Njini, 2018) using data from Statistics South Africa

The mining industry is also a large employer in South Africa with some 464 667 individuals (4.8% of employed individuals) directly employed by the sector in 2017, earning a total of R126 billion and contributing R10 billion towards pay-as-you-earn tax (Minerals Council South Africa, 2018). The Minerals Council South Africa (2018) estimates that each employee in the mining sector supports between five and ten dependants, thus the mining industry supports around 4.5 million people. The mining industry relies on high-level professionals across different fields whose diverse knowledge and skills, developed within the industry, contributes towards the country's innovation potential and intellectual property generation (Kane-Berman, 2017).

South Africa's mining industry plays an important role in generating national wealth and its abundance of mineral wealth, valued at roughly US$ 4.71 trillion (Baartjes and Gounden, 2011), has the potential to continue to create value for the country in the future. According to Monteiro and Njini (2018), citing Roger Baxter from the Minerals Council South Africa, the future of the mining industry will depend on its ability to reduce costs, improve safety and successfully implement innovation and technology. The financial sustainability of the mining industry in South Africa will depend on its ability to modernise and develop mechanised mining solutions, which will allow the mining industry to leverage optimal use of its limited resources against the economic potential of its mineral wealth (Singh, 2017). In this context, the envisaged modernisation will involve the improvement of current processes, technologies and skillsets and, where possible, the implementation of mechanised and/or automated equipment and eventually a move towards continuous operations (Singh, 2017).

1.1.2 Platinum mining in South Africa

Platinum demand

South Africa's platinum (Pt) and palladium (Pd) resources and their by-products, namely iridium, osmium, ruthenium and rhodium, are collectively named Platinum Group Metals (PGMs). PGMs have a number of technological, industrial, jewellery manufacturing and environmental applications. Figure 1.2 shows that there is an increasing demand for PGMs in the automotive industry since they are an important component of catalytic converters for various chemical reactions aimed at reducing levels of carbon monoxide, nitrogen oxides and unburnt hydrocarbons in exhaust gases (Rao and Reddi, 2000; Glaister and Mudd, 2010; Kraemer *et al.*, 2016). The electronic and glass industries have also shown increased uses of PGMs, while other applications of PGMs are as catalysts in fuel cells, for crude oil processing, and for the oxidation of ammonia (Rao and Reddi, 2000; Kraemer *et al.*, 2016). Additionally, medical applications for platinum include dentistry applications and anti-cancer treatment drugs (Rao and Reddi, 2000; Kraemer *et al.*, 2016).

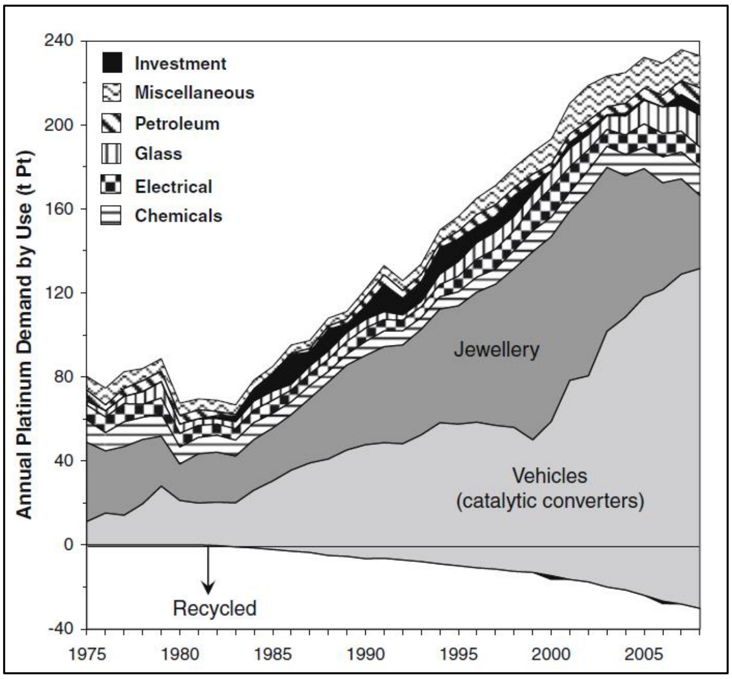

Figure 1.2 Global Platinum demand from 1975 to 2008 for various PGM applications (Glaister and Mudd, 2010)

Based on the trend of demand for PGMs over the past 30 years, the PGM demand is expected to continue increasing into the future. The demand for clean fuels such as hydrogen fuel cells, commitments from global leaders to minimise their carbon footprints, and a move towards more sustainable green economies will continue to drive this demand. Recent commitments by the international community culminating in the Paris Agreement on Climate Change saw pledges by the UK, France and Germany to phase out combustion engine diesel and petrol-fuelled vehicles by 2040.

In 2017, South Africa's platinum mining industry was the largest contributor to South African mining export sales, generating over a quarter of the total commodity export sales compared to other mineral commodities (highlighted in red in Figure 1.3) (Minerals Council South Africa, 2018). In 2016, South Africa exported most of its PGMs to Japan (27%), China (16%), the United Kingdom (15%) and the United States of America (14%) (Simoes and Hidalgo, 2011). Furthermore, the Japanese economy trends towards sustainable small-scale electricity generation and stricter emission standards and the drive towards fuel cell technology are predicted to increase demand for South African PGM exports (Department of Research and Information, 2016). South Africa also beneficiates a portion of its platinum production for locally produced catalytic converters, which represents high value exports, accounting for a fifth of its automotive exports in 2014 (Montmasson-Clair, 2016).

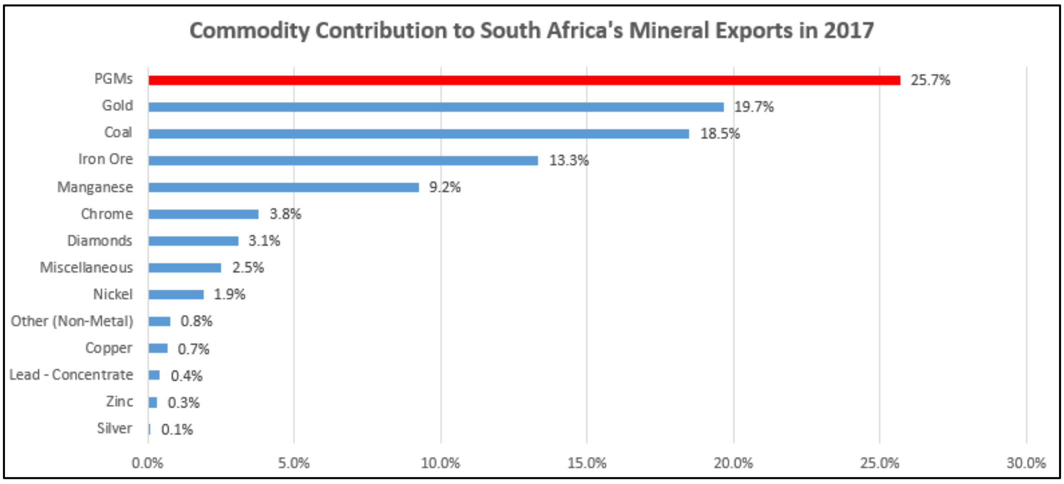

Figure 1.3 Major commodity contributions to South Africa's mineral exports in 2017 (as percentage of total rand sales) (Source: data from Minerals Council South Africa (2018))

Platinum supply

PGMs are hosted by the Bushveld Complex, a world-class repository that is the largest of four major layered igneous intrusions in the world (Cawthorn, 1999; Schouwstra *et al.*, 2000). This comparative advantage allows South Africa to dominate the global PGM production and supply (shown in Table 1.1 and Figure 1.4). Other countries such as Russia, Canada, Zimbabwe, and the United States produce much smaller amounts of PGMs. Table 1.1 further shows that South Africa has over 85% of the world's PGM reserves and that its deposits have a higher platinum to palladium ratio compared to PGM deposits elsewhere.

Table 1.1 PGM production, reserve and resources per PGM producing country for 2007

Country	Production			PGM	PGM
	Pt (t)	Pd (t)	PGMs (t)	Reserves (t)	Resources (t)
South Africa	165.83	86.46	310.92	63 000	70 000
Russia	27.00	96.80	138.30	6 200	6 600
Canada	6.20	10.50	20.20	310	390
Zimbabwe	5.30	4.20	11.00	-	-
Unites States	3.86	12.80	-	900	2 000
*World	212	219	509	71 000	80 000

Source: Adapted from (Glaister and Mudd, 2010)

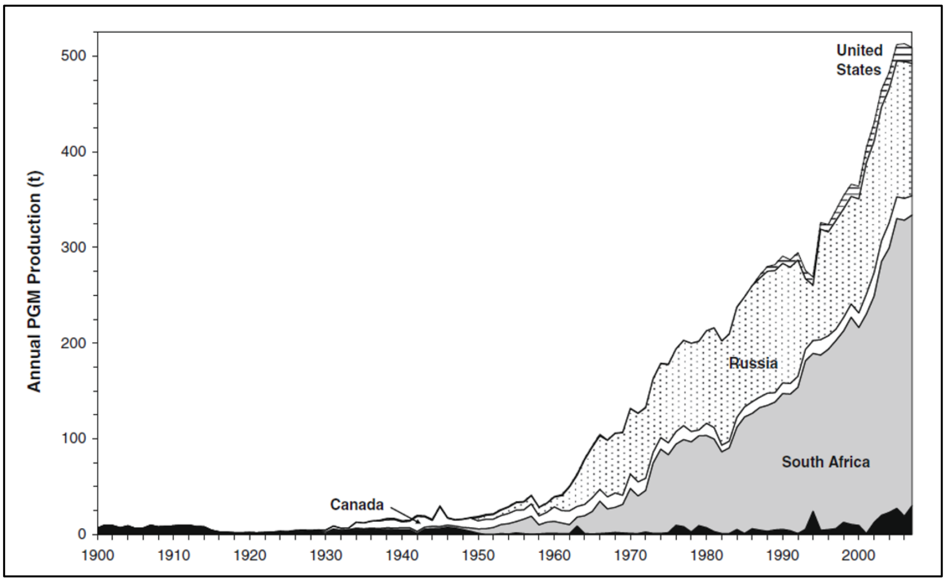

Figure 1.4 Historical global PGM production (tonnes) from 1900 to 2008 (Adapted from (Glaister and Mudd, 2010))

The Bushveld Complex covers an area of over 65 000 km^2, has a thickness of around 7 km to 9 km, and has a series of laterally continuous, fractionated silicate and mafic magma layers, rendering it unique (Cawthorn, 1999; Schouwstra *et al.*, 2000). Figure 1.5 shows the geological map of the Bushveld Complex in South Africa and the three discrete geographical areas, namely the Western Limb, Eastern Limb and the Northern Limb (Cawthorn, 1999; Kraemer *et al.*, 2016). The largest concentration of PGMs are hosted in the mafic magma layers of the upper critical zone of the Bushveld Complex in the Upper Group 2 (UG2) reef, the Merensky reef and the Platreef (Cawthorn, 1999; Kraemer *et al.*, 2016). The UG2 and Merensky reefs are unique, as they are narrow tabular ore bodies with a typical seam height of between 1 m and 1.5 m that extend to great depths and are mostly undisturbed and homogenous (Jager and Ryder, 1999; van den Berg, 2014). Geological losses such as potholes, iron rich ultramafic pegmatoids and various structures on these reefs account for 20% to 30% of the resource (van den Berg, 2014). These reefs are characterised by gentle dips between 9° and 22° towards the centre of the complex (Viljoen, 1999).

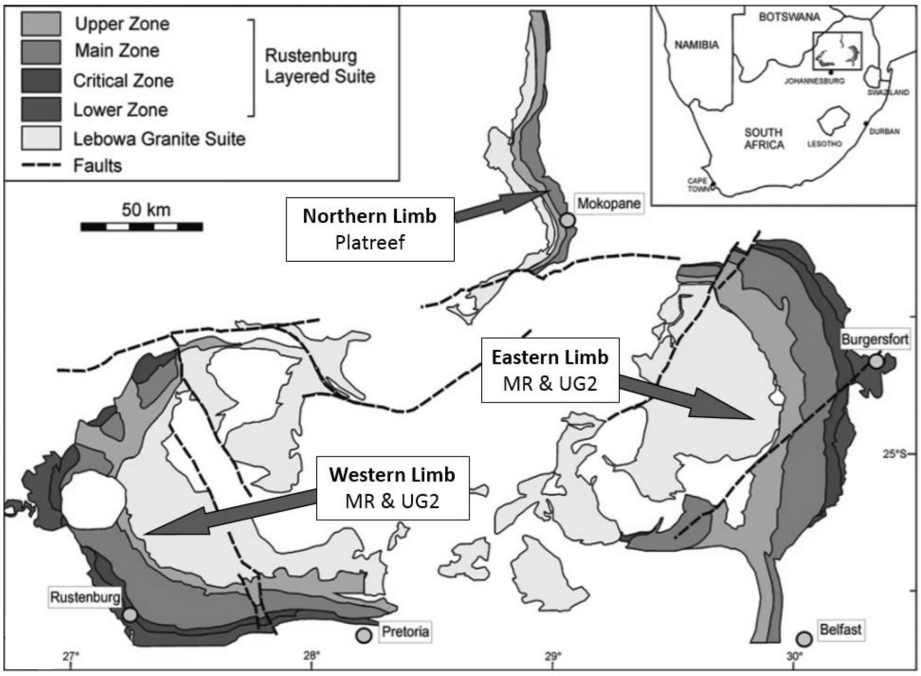

Figure 1.5 The geological map of the Bushveld Complex and its location within South Africa (Adapted from Kraemer *et al.* (2016))

Challenges facing the South African platinum mining industry

In 2014, approximately 60% of South Africa's platinum production was mined using conventional cyclical drill and blast mining methods, with the remaining 40% of production mined using open-pit or underground mechanised methods (van den Berg, 2014). Conventional mining is the most prevalent because it yields good shaft head grades due to the low levels of dilution (Egerton, 2004). In conventional mining methods, the ore body is accessed from a shaft through off-reef developments such as haulages, crosscuts and drives that enable development waste to be hoisted independently from the reef (Egerton, 2004). Extraction of the orebody is then done through stoping in a grid pattern, using labour-intensive drill and blast methods, which mostly employ hand-held jackhammers for drilling and use explosives for blasting at the end of the shift (Egerton, 2004). Support is installed in the form of roof bolts or support pillars that are not extracted (Egerton, 2004). The panels are cleaned using scraper winches, and loaders are used to transfer the rocks into locos and hoppers that transport the rock to the shaft to be hoisted to the surface (Egerton, 2004).

Conventional underground platinum mines typically have a large spatial footprint, and each year approximately 30 000 000 m^2 of ground is mined and accessed through approximately 800 km of newly developed tunnels and 10 000 km of existing tunnels (Jager and Ryder, 1999). These mines are typically labour-intensive, and the employees are continuously exposed to the hazards of deep level underground mining as the face advances and new geological structures are exposed by mining (Jager and Ryder, 1999). The geotechnical hazards experienced in these deep-level mines may lead to hazardous falls of ground and are unique in their magnitude and severity (Jager and Ryder, 1999). They often occur because of (Jager and Ryder, 1999):

- The strong but brittle host rocks that are highly fractured when exposed;
- Weak bedding planes in the exposed hanging-wall that are not always visible by inspection; and
- Faulting that generates seismicity when large areas are extracted - leading to hazardous falls of ground.

van den Berg (2014) showed in Figure 1.6 that productivity for stoping and development in a large conventional platinum mine exhibited a steady decline between 2009 and 2013 and stated that conventional mining methods no longer provide a viable business case, especially for new mining projects, mine extensions and replacement projects and that different mining methods should be investigated. A different study on a platinum mine showed that mine crews spend less than 50% of their shift at the stope face as mining depths increase and mining crews spend more time travelling to the stope face, potentially also contributing towards a decline in productivity (Rupprecht, 2017).

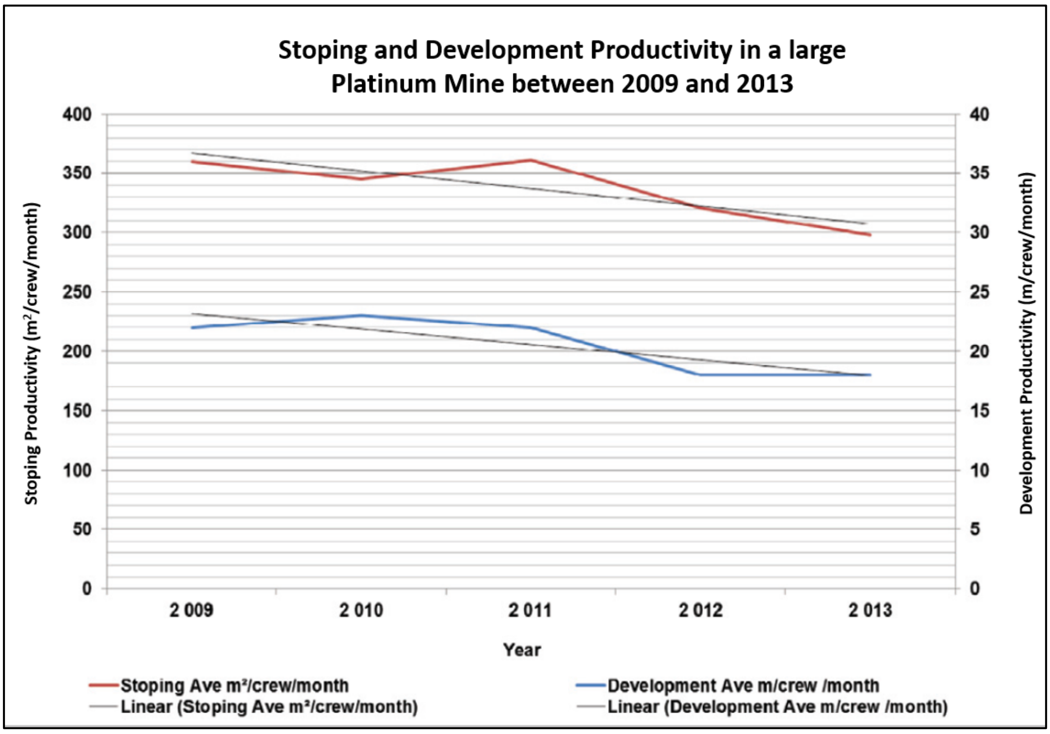

Figure 1.6 Productivity in a conventional platinum mine between 2009 and 2013 (van den Berg, 2014)

In 2018 Impala Platinum announced the retrenchment of 13 000 employees over the next two years (Seccombe, 2018). Lonmin has already retrenched over 3 000 employees in 2018 and plans to retrench a further 8 900 employees over the next two years (Lechela, 2018). High operating costs and low platinum prices led to non-profitable platinum shafts, with Impala planning to close or sell five of its shafts (Seccombe, 2018). These challenges are echoed by the statements from two platinum executives at a 2017 mine conference, who claimed that 70% of the South African platinum mines were running at a loss (Rupprecht, 2017). Most of the above-mentioned challenges presented by conventional drilling and blasting mining methods in the platinum mining industry are summarised in Figure 1.7 (Rupprecht, 2017).

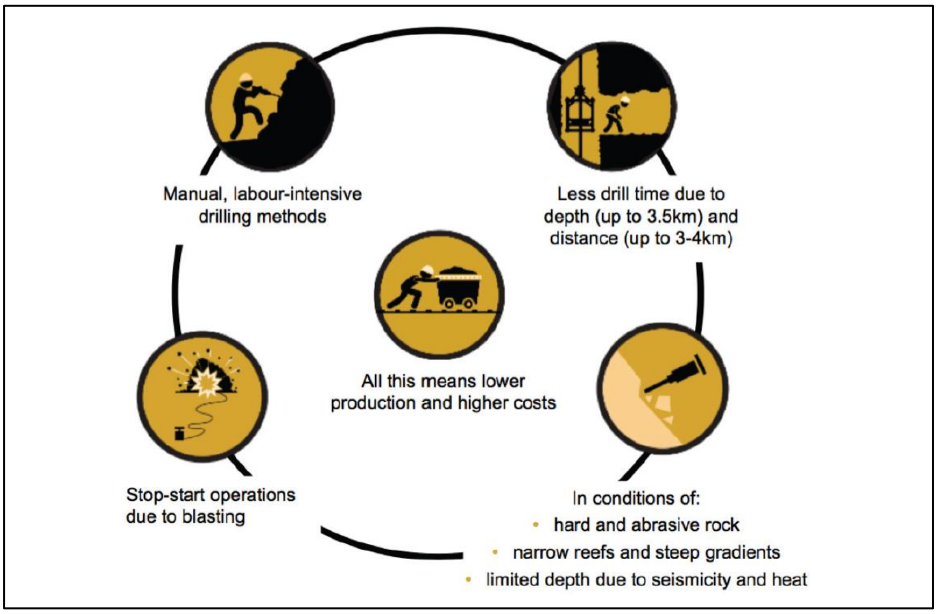

Figure 1.7 Illustration of conventional drill and blast cyclical mining and its associated challenges (Rupprecht, 2017)

Finally, water and energy supply and costs have thus been identified as one of the major risks facing the South African mining industry (Ernst and Young Global Limited, 2014; Nguyen *et al*., 2014; Ernst and Young Global Limited, 2016; PricewaterhouseCoopers, 2016). Access to water and energy is essential for platinum mining operations since mining at great depths results in exposure to steep geothermal gradients (Minerals Council South Africa, 2017). The virgin rock temperature at depths of greater than 2 km can be as high as 70°C in the Bushveld Complex (Minerals Council South Africa, 2017). Water is used at every stage of the underground platinum mining process for cooling and pneumatic systems and on the surface at concentrators and smelters (Haggard, 2015). Electricity at conventional deep-level underground platinum mines is used for ventilation, cooling, hoisting ore, dewatering the mine, and lighting the working areas (Cornish and Kotze, 2015). Thus, underground mining requires a continuous supply of water and energy and any restrictions and/ or cost price volatility may have a negative impact on the mining operation and its profitability (PricewaterhouseCoopers, 2016). Mining companies and projects require long-term planning and capital allocation considerations, and any substantial deviations from typical and planned electricity tariff increases could have a negative impact on current and future mining projects.

1.1.3 Modernisation of the platinum mining industry

Industry, government, research and educational organisations have embarked either in their individual capacity and/or through the collaborative Mining Phakisa initiative on various modernisation drives in order to address structural and immediate challenges plaguing the mining industry (Minerals Council South Africa, 2017; Singh, 2017). The aim is to extend the life of platinum mines and transform the mining industry (Minerals Council South Africa, 2017; Singh, 2017), and to ultimately mine the ore exclusively in the most cost effective way (Egerton, 2004).

A 2015 study by the Minerals Council South Africa (representing most of the mining companies in South Africa) resulted in the model illustrated in Figure 1.8 that forecasts PGM tonnes mined per year (assuming a platinum price of US$ 1100 per ounce of PGM) (Fourie *et al.*, 2017a; Rupprecht, 2017). The model predicts that payable platinum reserves mined conventionally will mostly be depleted by 2025 (Fourie *et al.*, 2017a; Rupprecht, 2017). The model further shows that through the implementation of mechanised and continuous mechanised mining methods, the extraction of payable reserves could be extended beyond 2040 (Fourie *et al.*, 2017a; Rupprecht, 2017). This reinforces the need to, where possible, shift away from labour-intensive and costly conventional mining methods to more modern mining methods such as mechanised and continuous mining operations (Fourie *et al.*, 2017a; Rupprecht, 2017). Singh (2017) envisaged that modernised conventional mining (increased mining efficiencies and improved mining processes of current conventional mining methods and technologies) and mechanised and autonomous mining technologies will potentially remove people from the underground mining face, reducing their exposure to underground hazards such as rock falls, while allowing the efficient extraction of the reef through the reduction of waste mined.

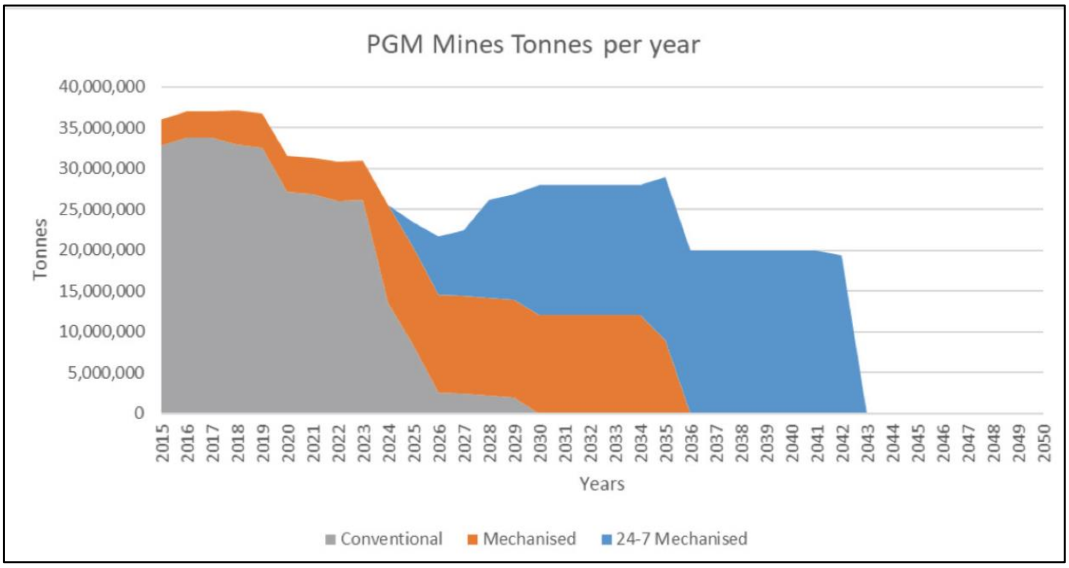

Figure 1.8 Production projections of the South African platinum mines using conventional, mechanised and continuous mining methods(Fourie *et al.*, 2017a; Rupprecht, 2017) - source data from the Minerals Council South Africa

1.2 Problem Statement

In light of the current mining modernisation drive to save the platinum mining industry, it is unclear how the implementation of modernisation of mining operations will impact water and energy consumption and costs. Failure of the mining sector to carefully manage its consumption of water and energy may have an adverse effect on its social licence to operate (Ernst and Young Global Limited, 2014). The challenges related to water and energy are amplified by the fact that they are vital resources for the sustainability of human life and production and can therefore not be separated from the environment (Parker *et al.*, 2016). From an ecological perspective, water and energy are less "economic resources" and more "common goods", which have greater value in their use than their exchange (Parker *et al.*, 2016).

This research report investigates the consumption and associated cost implications from the implementation of modernisation in the platinum mining industry with respect to water and energy. Modernised narrow reef mining operations include modernised conventional operations, drill and blast mechanised mines and non-explosive continuous operations.

1.3 Research Question

The main research question that this study aimed to address is:

> *What are the consumption and cost implications with respect to energy and water associated with the implementation of modernisation in the narrow reef platinum mining industry?*

In order to answer this question, the following sub questions were answered:

i. *What is the consumption and resulting cost implications with respect to water and energy that may result from modernising conventional mining operations (with increased mining efficiencies and improved mining processes and technologies)?*

ii. *How much water and energy does current modern underground platinum mining operations such as current mechanised mining operations consume compared to a typical conventional mining operation and what are the associated cost implications?*

iii. *What is the forecasted water and energy demand and resulting costs for the narrow reef platinum mining industry associated with the implementation of modernisation?*

1.4 Research Objectives

Based on the research questions, the following research objectives were identified:

a) Quantify the water and energy consumption and potential cost implications that may result from modernising conventional operations (with increased mining efficiencies and improved mining processes and technologies);

b) Quantify the water and energy consumption and potential cost implications that may result from extracting narrow platinum reefs through current modernised mining operations such as mechanised mining operations; and
c) Estimate the future consumption requirements and resulting costs with respect to water and energy associated with modernising the narrow reef platinum mining industry.

1.5 Significance of the Research

This research is important as it is expected that water and energy risks for mining companies will continue to grow in the face of continued droughts that South Africa has experienced as well as electricity supply shortfalls, above-inflation electricity price increases and competition for electricity and water resources from other industries, governments and communities (Ernst and Young Global Limited, 2014; PricewaterhouseCoopers, 2016).

1.6 Research Methodology

The research design used was literature reviews and survey-based research through semi-structured interviews. Data was collected from various mine sites. Additionally, discussions with mine personnel as well as underground visits were conducted. An ethics waiver (shown in Appendix A) was obtained from the university. Furthermore, a desktop literature review was undertaken using peer-reviewed literature, mine reports, equipment specification and because of the novel nature of this research, popular media from reliable sources.

1.7 Chapter Outline

Chapter 1 focuses on formulating the research question by providing a brief background on the research scope, namely platinum mining in South Africa and the challenges that threaten the sustainability of the platinum mining industry – of which energy and water supply are integral challenges. The purpose of the research is stated in a problem statement, from which the research questions and objectives were formulated. The significance of the study, the methodology and the research design are summarised. Chapter 2 focuses on the research design and methodology used in the study. It describes the data sources, data collection processes and how the data analysis was undertaken. Research limitations, assumptions and ethical considerations are provided.

Chapter 3 is a literature review on the global landscape of energy and water with a focus on global energy and water challenges. Chapter 4 is a literature review that focuses on the South African energy landscape and the role that energy plays within the platinum mining industry. It highlights the impact that recent electricity price increases have on the mining industry and the impact that a further carbon tax could have on the electricity price, further potentially increasing mining input costs. It further establishes the current state of knowledge of energy consumption at conventional platinum mining operations. Chapter 5 is a literature review on the South African water landscape and its importance to the South African platinum mining industry and highlights the challenges regarding the current constrained state of available water resources. It further establishes the current state of knowledge of water consumption at conventional platinum mining operations. Chapter 6 is a literature review to establish the current state of knowledge of South African modernised platinum mining methods as well as their water and energy consumption requirements.

Chapter 7 focuses on the results obtained from the analysis of the acquired data in order to establish the current and potential future consumption and cost implications from modernising underground narrow reef platinum mining. Chapter 8 concludes the research and suggests recommendations for future research work.

2 METHODOLOGY

2.1 Introduction

The purpose of the study was to determine the consumption and resulting cost implications with respect to water and energy that may arise from the implementation of modernisation in hard rock narrow reef platinum mining. Modernisation is understood to include:

a) The modernisation of current conventional mining operations through the implementation of new or improved technologies and operational processes without altering the conventional mining method (Minerals Council South Africa, 2017; Fourie *et al.*, 2017a; Singh, 2017; Fraser, 2017);
b) The implementation of mechanised drill and blast mining systems and machinery that is either operator driven, remote controlled or autonomous; and
c) The implementation of continuous autonomous mechanised mining systems that employ rock cutting or non-explosive rock breaking techniques (Minerals Council South Africa, 2017; Fourie *et al.*, 2017a; Singh, 2017).

The research methodology was thus designed to achieve the research objectives and thus answer the research questions as outlined in Chapter 1. The water and energy consumption of conventional operations were used as a baseline for this study. Water and energy consumption of modern mining operations were compared to this baseline. This chapter outlines the research design, methodology, limitations, and data used to achieve the research objectives.

2.2 Research Design

Two research methods were used in this study, namely a literature review and survey-based research through semi-structured interviews. The literature review was undertaken to understand the existing body of knowledge with respect to water and energy challenges, water and energy consumption at mines, modern mining methods and consumption information that is publicly available with respect to the implementation of modernisation in mines. For the survey-based research through semi-structured interviews, standardisation was achieved through the compilation of a set of core survey questions and data requirements. Mine visits and semi-structured interviews with on-mine engineers were undertaken to allow for direct interaction with participants and the flexibility to ask follow-up questions to gain a better understanding of the data and how it was measured. The mine visits also mitigated the risk of survey questions being completed incorrectly and allowed for the validation of data received. A disadvantage of employing this research design is that smaller sample sizes reduce the applicability of the results to the general population.

2.3 Methodology

In order to fully understand the potential impacts of mine modernisation on water and energy consumption and costs, in particular for narrow reef platinum extraction, it is important to understand the status quo of water and energy consumption in mining. In this study the potable water and energy consumption of typical conventional operations were used as a baseline. All three forms of modernisations, namely modernised conventional mining, mechanised mining and future continuous non-explosive mining were compared to the baseline conventional operations. To achieve the research objectives, the following methodology was applied:

1. A literature review was done to gather information on:
    a) The current state of knowledge with respect to the global, local and on-mine status quo of water and energy consumption of platinum mining operations;
    b) The quantification of water and energy consumption for current platinum mining operations;
    c) The current state of knowledge on modernised mining; and
    d) The quantification of water and energy consumption for modern mining operations, especially modern conventional operations.

2. For consumption and cost implications for modernising conventional operations:

a) Modernisation trials were confidential at the time of writing, hence, publicly available water and energy data from modernisation trials at a modernised conventional stope was analysed to estimate consumption and cost implications resulting from the implementation of improved drills at the site. Raw data could not be accessed due to confidentiality.

3. For consumption and cost implications for current modern mining operations such as mechanised operations:
   a) A survey with semi-structured interviews was undertaken to acquire potable water and energy consumption data, between 2013 and 2017, from several platinum conventional and mechanised mining operations;
   b) By analysing the data, a status quo assessment was established of the potable water and energy consumption at the research sites;
   c) Representative potable water and energy consumption values were determined for conventional and mechanised mining operations; and
   d) Using the consumption values identified, the potential financial implications were determined.

4. For consumption and cost implications for future modernised operations:
   a) A theoretical production forecast for the platinum industry was used to forecast energy and potable water consumption for the platinum mining industry; and
   b) Publicly available price forecasts for energy and potable water were used to estimate the cost implications from a water and energy perspective resulting from the implementation of modernisation in platinum mining industry.

2.3.1 Data

Data sources

The sample unit in this study was an underground narrow reef operating platinum mine within the Bushveld complex that employs conventional or mechanised mining. The sample size comprised of 17 mining operations from three mining companies that were willing to participate in the study. The study samples were from Impala Platinum, Africa Rainbow Minerals and Northam Platinum. Impala Platinum provided information for 16 conventional mining operations from its Rustenburg operations. Only 14 of the mines were operational and were analysed in this study. The other two operations were on care and maintenance and were excluded from the analysis as they were not representative of an operational mine. Two Rivers provided information for two operational mechanised operations. Northam Platinum provided information for its mechanised Booysendal North Mine operation.

The geographical locations with respect to South Africa and the Bushveld Complex of the data samples are shown in Figure 2.1. The red dots represent the mining companies used in the study.

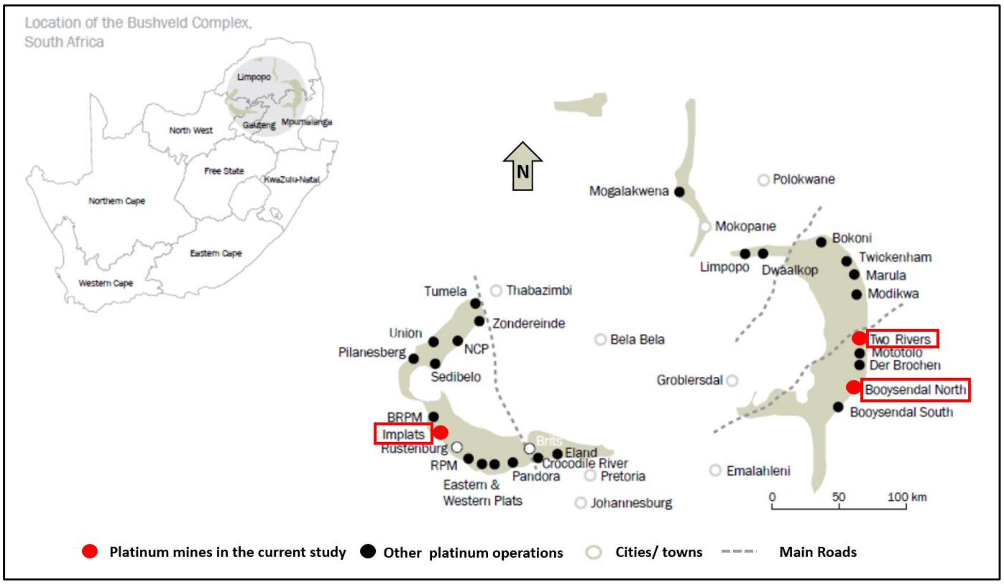

Figure 2.1 Platinum mines hosted in the Bushveld Complex (Minerals Council South Africa, 2020)

Impala Platinum Rustenburg operations are conventional mining operations and are all located in the Western limb of the Bushveld complex, near Rustenburg. Both Merensky and UG2 reefs are mined jointly at the operations and have a vertical separation of 125 m in the south and approximately 45 m in the north (Impala Platinum, 2018a). The reefs dip between 10° and 15° to the east (Impala Platinum, 2018a).

The predominant mining method used at the operations is the conventional breast mining method (Impala Platinum, 2018b). At two of the operations, a mechanised bord and pillar mining method, using handheld drilling machines and low profile LHD loaders, is used in selected Merensky reef sections (Impala Platinum, 2018a). Two operations use trackless mobile machines are used for primary development. The current average mining depth of most operations is around 800 m. The deep operations have a vertical shaft depth of between 668 m and 1650 m and the shallow operations (of which one is a decline) have depths of between 195 m and 496 m. The typical extraction widths for Merensky and UG2 reefs are 1.3 m and 1.1 m respectively (Impala Platinum, 2018a).

Two Rivers Mine, a joint venture between Africa Rainbow Minerals (ARM) (55%) and Impala Platinum (45%) provided information for its two fully mechanised operations located in the Eastern Bushveld approximately 35 km south east of Burgersfort in Mpumalanga (Impala Platinum, 2018b). The UG2 reef is currently exploited at the operations and dips between 7° and 10° to the west (Impala Platinum, 2018b). The mining method used at the operations is the bord and pillar mining method with decline shaft systems used to access the reef (Impala Platinum, 2018b). The average mining depth at the Two Rivers operations is 450 m. The typical extraction width for the UG2 reef is 1.8 m, with a reef thickness of 1.2 m to 1.4 m (Impala Platinum, 2018b).

Booysendal, a subsidiary of Northam Platinum Limited, provided information for one of its fully mechanised mining operations. It is located in the Eastern Bushveld, 35 km west of Mashishing (formerly Lydenburg) in Mpumalanga. The UG2 and Merensky reefs are currently exploited at the operation and dips approximately 10° to the west (Northam Platinum Limited, 2019). The mining method used at the operation is trackless bord and pillar with ramp decline systems used to access the reef (Northam Platinum Limited, 2019). The average mining depth is 450 m. The typical extraction width for the UG2 reef is 2.1 m, with a combined reef thickness of approximately 1.5 m. The mineralised Merensky Pyroxynite is approximately 1.1m thick with a mining cut of 1.9 m (Northam Platinum Limited, 2019).

Data collection

The sampling frame in the study was underground mining activities. The sample frame excluded processing and smelting activities. The data obtained from the sampling frame was energy and potable water consumption. With regards to energy data, electricity and diesel consumption data was obtained. With regards to water, the volume of potable water purchased from the municipality was obtained. Recycled water or water extracted from underground aquifers and run-off was excluded.

Survey participants provided information on underground potable water and energy consumption for a period of four or five years from 2013 to 2017. Data from four or five years is a good representative period that shows the current trend in the data and is more reliable than data from only one year, because data from one year could be anomalous and not representative of the general trend.

The data obtained from each of the operations comprised of monthly consumption figures over the data range of:

a) Potable water purchased from the municipality (in litres);
b) Electricity (kW) purchased from ESKOM;
c) Diesel consumption (litres); and
d) Production data (waste and reef broken in Tonnes).

Since the intent of data was to demonstrate water and energy consumption, the measurement units a to c were chosen since they are indicators of water and energy consumption. The production data is required to normalise the potable water and energy consumption data to unit potable water and energy consumption, to enable comparisons.

2.3.2 Analysis

Modern conventional mining

To estimate the consumption and cost implications resulting from modernising conventional operations with respect to water and energy, publicly available results from a drilling trial at a modernisation test stope at Anglo American Platinum from Fourie *et al*., (2017b) were used. Due to confidentiality of the trial, raw information was not available. Pneumatic drills are widely used at typical conventional underground operations and was thus used as a baseline to compare other drill technology to. The following calculations were applied to the Anglo American Platinum trial results to estimate efficiency and cost implications with respect to water and energy:

a) The average water costs per panel per day was calculated for each of the drills using the 2016/17 Rand Water tariff of R11.40/kL;
b) The water costs per panel per day for each of the drills were compared to water costs for pneumatic drill; and
c) The percentage consumption gains or losses and the resulting cost implications were calculated for each of the drills compared to the pneumatic drill.

Mechanised mining

In order to estimate the consumption and cost implications resulting from mechanised mining operations compared to conventional operations, representative energy and potable water consumption values for conventional and mechanised platinum mining operations acquired in the survey was analysed as follows:

a) From the monthly data, yearly consumption and production values were calculated;
b) Yearly electricity (kWh) and diesel (l) consumption was then converted to energy in GJ using a conversion factor of 0.0036 for electricity and 0.0348 for diesel since:
    i. *1kWh electricity = 0.0036 GJ of energy;* and

ii. *1l diesel = 0.0348 GJ of energy.*

c) Diesel energy in GJ was added to electrical energy in GJ to provide a total energy consumption value. Other forms of energy such as explosives or hydropower were excluded, as these were not available and in the opinion of the mining personnel were not significant contributors;

d) Since the operations vary in depths and scale of operation, in order to normalise the data for comparative purposes, the energy consumption (GJ) was divided by the production data (tonnes of rock broken) to provide a unit energy consumption for comparison against other operations;

e) Similarly, the total potable water consumption (l or m^3) was converted to kl and divided by the production data (tonnes of rock broken) to provide a unit potable water consumption for comparison against operations;

f) The average over the data range of unit potable water and energy consumption was calculated (Appendix D presents annual data for each operation). By averaging over the data range, missing records are addressed.

g) Yearly and four or five-year average consumption data was graphically analysed for trends and patterns;

h) From the data, average unit energy and potable water consumption was estimated for conventional and mechanised platinum mining operations; and

i) Using average annual potable water and energy tariffs between 2013 to 2017, the average unit potable water and energy costs were estimated to evaluate cost implications.

Future modernised mining

To estimate consumption and cost implications for future modernised operations:

a) The predicted platinum payable reserves that will be unlocked as a result of the implementation of modern mining methods that were modelled by the Minerals Council of South Africa and was shown in Figure 1.8 is currently the best available knowledge of future modern mining methods in the platinum industry. This theoretical production forecast for the platinum industry was used to forecast energy and potable water consumption for the platinum mining industry. An assumption was made that future continuous mechanised mining will use, at most, the same unit energy and unit potable water consumption as current mechanised mines, and thus both were considered as mechanised mines for this study.

b) The average unit energy and potable water consumption estimated for conventional and mechanised platinum mining operations from the analysis of mechanised operations was used to estimate the future energy and potable water demand for the platinum mining industry;

c) Publicly available price forecasts from the integrated resource plan were used to estimate the cost implications from an energy perspective resulting from the implementation of modernisation in platinum mining industry; and

d) Publicly available potable water tariff information for potable water purchased from Rand Water from 2008 to 2017 was extrapolated linearly to 2043 and was used to estimate the cost implications from a potable water perspective resulting from the implementation of modernisation in platinum mining industry.

2.4 Ethical Considerations

An ethics waiver was obtained from the university to acquire the data for this study (shown in Appendix A). All the mining companies granted permission to use and publish the data and outcomes obtained for this study (Appendix B).

2.5 Research Limitations

Some research limitations were discussed throughout the methodology and analysis sections, however, the most important limitations that impacted the methodology, analysis and interpretation are discussed below, namely:

- The research sample size was limited to 17 underground narrow reef platinum mining operations (3 mechanised and 14 conventional) from 3 platinum mining companies and did not include all the underground narrow reef mines in South Africa. Due to the small sample size, it is understood that the applicability of the results to the general underground platinum mining industry is reduced, however, it seems plausible that the results may be reasonably generalised to the population but should be further verified.

- It should be noted that the various mining operations used in the case study have various mining depths, production outputs and mining methods, with various degrees of improvements of energy and water efficiencies which could impact the results. The water and energy consumption data were thus normalised by production outputs. Furthermore, to minimise the impact of these factors, when comparisons between conventional and mechanised operations were made, only conventional operations with similar characteristics (for example, depth, refrigeration and phase profile) to the mechanised operations were selected.
- This research was limited to the total energy and potable water requirements for underground mining activities and did not consider energy and water consumption associated with concentration and smelting, nor energy and water requirements of individual underground mining activities.
- This research was limited to potable water purchased from the municipality and did not consider the dominant water sources used for underground activities such as bulk, raw and effluent water purchased from water boards. The average unit water consumption obtained in this study is thus not indicative of the overall water consumption underground but provides an indication of more expensive unit potable water consumption underground.
- Water tariff data for this research was limited to water tariff information provided by the conventional Rustenburg operations for potable water purchased from Rand Water. At the time of writing, water tariff information was not provided by the mechanised operations. It is understood that water tariffs are variable, unpredictable and complex and that there are many factors involved in water tariff pricing such as the municipality water is purchased from, distances to water resources, water infrastructure, water pollution costs, and the location of mines. However, for this study the Rand Water tariffs were used to estimate water costs for all the operations in the study.
- The forecasts used in this study were limited to the best available knowledge at the time of writing. The raw data for the theoretical production forecasts and the forecasted electricity tariffs were not available and were thus digitised

from the publicly available graphs. Price forecasts for diesel were not available and hence energy tariff forecasts were limited to publicly available electricity tariff forecasts. Water tariff forecasts were also not available, hence the water tariff information provided by the Rustenburg operations for potable water purchased from Rand Water from 2008 to 2017 was extrapolated linearly to 2043 to provide a forecast.

2.6 Conclusion

This chapter focused on the methodology used to undertake the research. The research design was a literature review and a survey with semi structured interviews. The data used in the research was discussed and included data from the literature review and data collected from the platinum mining operations in the study. The geographical location of the platinum operations was presented. The methodology and data analysis were discussed and considered different modernisation scenarios, namely modernising a conventional operation, mechanised operations and future mechanised operations that include continuous mining. Research limitations that impacted and influenced the interpretation was discussed throughout the methodology section with the most important limitations summarised under the research limitation section.

3 ENERGY AND WATER – A GLOBAL PERSPECTIVE

3.1 Energy

An energy system entails both the conversion and utilisation of energy (Mogodi, 2012). Energy conversion encompasses the processes that locate, extract, transport and store energy (Tshisekedi, 2009). Energy utilisation deals with the processes that underpin the consumption of energy (Mogodi, 2012). The sources of energy can be classified as renewable and non-renewable, with renewable sources of energy including wind, solar, hydro sources of energy and non-renewable sources of energy including hydrocarbon-based (for example, petroleum and natural gas), coal and nuclear (Tshisekedi, 2009). The energy flow further differentiates energy into primary, secondary and final forms (Mogodi, 2012). Primary energy is obtained through direct utilisation of primary sources, such as coal and natural gas (Tshisekedi, 2009). Secondary energy is obtained through conversion of primary energy, such as refining crude oil to various petroleum products (Tshisekedi, 2009). Final energy is defined as the last step in the energy flow and deals with quantities of energy consumed and the efficiency of these processes (Tshisekedi, 2009).

3.1.1 Energy and the economy

Access to energy is important to the economic development of a country as it underpins industrial and social development such as poverty alleviation and social wellbeing (Vivid Economics, 2013; Ritchie and Roser, 2018). As a critical input to produce all goods, services delivered and activities, energy contributes towards economic growth and maintaining and improving the standard of living for the world's rapidly growing population (Stern, 2011; Yergin and Gross, 2012; Vivid Economics, 2013). For most countries (except for major oil exporters), the energy sector directly contributes a relatively small amount in terms direct employment, linkages to industries that supply the sector and profit generation (Yergin and Gross, 2012). However, indirectly the energy sector impacts on most of the economy and factors such as energy supply interruptions, electricity supply disruptions and shortages and energy price volatility have a measurable impact on economies (Yergin and Gross, 2012). Higher energy prices are generally associated with decreased consumer spending and lower consumer confidence, which has a negative impact on economic growth (Yergin and Gross, 2012).

Globally, the quality of electricity supply has been linked to GDP per capita, emphasizing the importance of both the availability and the reliability of electricity supply for enabling economic growth (Stern, 2011; Castellano *et al.*, 2015). Vivid Economics (2013) found that energy consumption and economic growth are linked even though it unclear which of these two metrics is the causative. Similarly, Vivid Economics (2013) found that energy productivity (GDP per unit of energy consumed) and economic growth are also linked, but that any of the two metrics may be the causative. Between 1979 and 2010, in resource scarce developed economies, such as Japan, France and the United Kingdom, energy productivity decoupled from the economic growth as shown in Figure 3.1 (Vivid Economics, 2013). Figure 3.1 shows that the GDP per capita flattens and in some cases is decreasing, whilst energy productivity increases. The rationale behind this decoupling has been largely attributed to movement away from energy intensive industries to service-related activities or that these economies produce more products using less energy (increased energy efficiency) (Vivid Economics, 2013). Energy efficiency is not only one of the factors or variables that are beneficial to improving energy productivity, but is a cost effective way to reduce carbon emissions and an economy’s exposure to energy price shocks (sharp increases) that, if large enough, have been shown to result in market contractions and recessions (Vivid Economics, 2013).

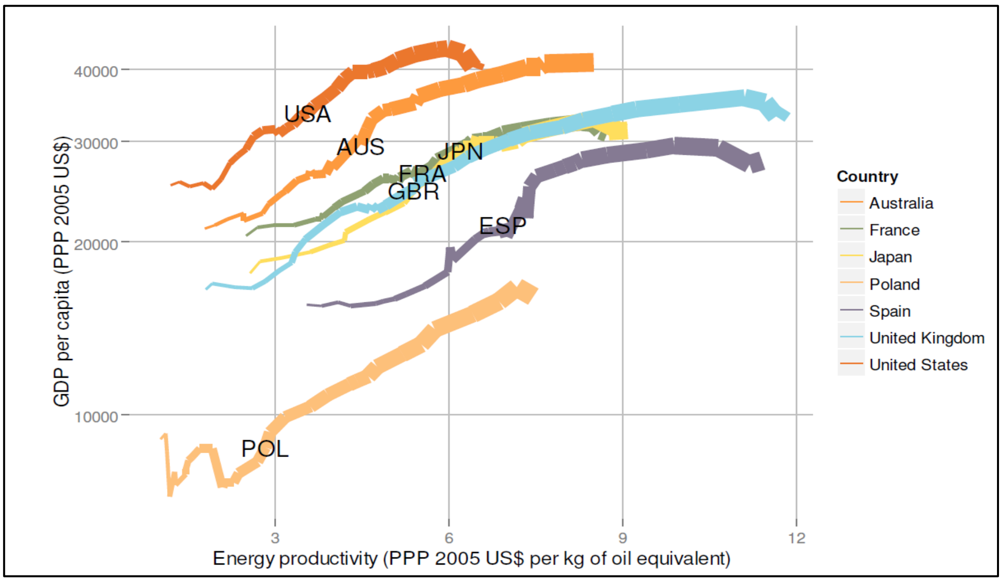

Figure 3.1 Energy productivity against GDP per capita between 1979 and 2010 (Vivid Economics, 2013)

The global economic crisis in 2008 negatively affected the economic growth aspirations of many countries. However, despite its severe impact on the global economy, the energy sector showed resilience and even modest growth driven by increased energy demand from the developing nations (Yergin and Gross, 2012; Vivid Economics, 2013). Rapid economic growth experienced in the last two decades has resulted in a drastic increase in global energy consumption, dominated by natural gas, oil and coal (hydrocarbon-based) as sources of primary energy, as illustrated in Figure 3.2 (Ritchie and Roser, 2018). Although there is progress to introduce various renewable sources in the global energy mix, most of the global energy consumption is still dominated by non-renewables (Ritchie and Roser, 2018). The energy mix is constantly evolving (Stern, 2011). Developed economies favour diverse sources of energy and grow the share of renewables in their energy mix (Stern, 2011). Stern (2011) and Vivid Economics (2013) found that countries that reduce their dependence on hydrocarbon-based energy sources have seen accelerated economic growth. Developing countries are highly reliant on hydrocarbon-based energy sources (Stern, 2011).

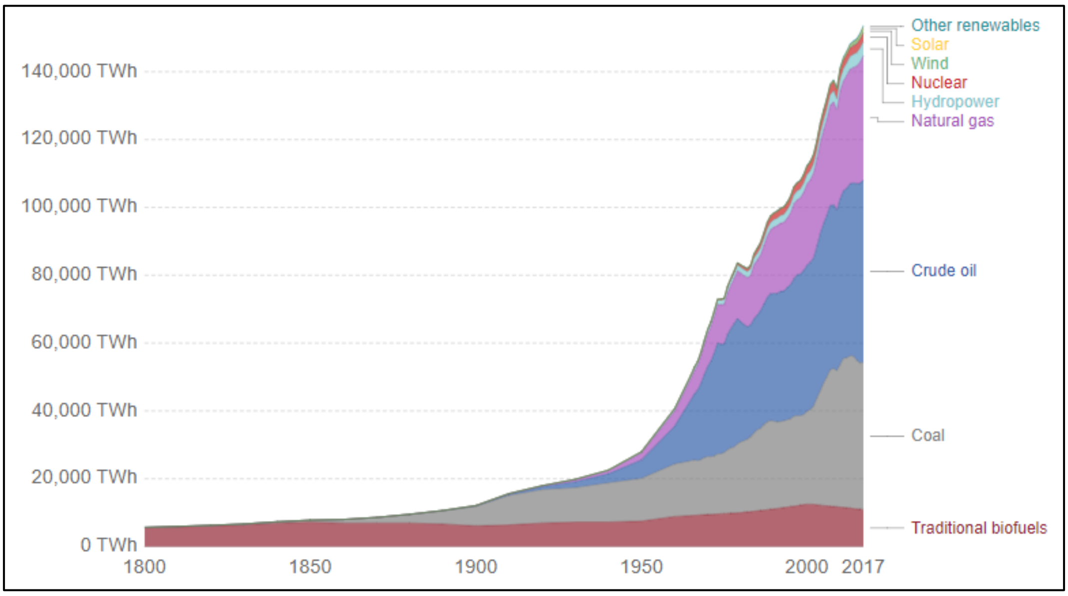

Figure 3.2 The global primary energy consumption and sources from 1800 to 2017 (in TWh per year)(Ritchie and Roser, 2018)

Globally, energy efficiency gains have also been realised through the utilisation of higher quality fuels coupled with technological advances and resulting in a reduction of energy resources constraints on GDP and economic growth (Stern, 2011). Energy quality is an economic concept describing the relative usefulness or productivity per heat equivalent unit of various fuels (Stern, 2011). Electricity and natural gas are the highest quality energy fuels, followed by oil, coal, wood and biofuels (Stern, 2011). Technological progress and structural economic changes towards service intensive economies have resulted in a rise in the consumption of the highest quality fuels: electricity and natural gas (Stern, 2011).

3.1.2 Energy transitions

Over a century ago, the energy system underwent a major transition when the internal combustion engine and electricity made its debut (World Economic Forum Global Future Council, 2018). This energy transition changed the way we work, live and interact, and is responsible for bulk of economic and technological progress that fuelled economic growth in 20th century (World Economic Forum Global Future Council, 2018). However, the carbon intensive energy system that fuelled this growth had negative externalities for the environment in the form of

Carbon emissions (World Economic Forum Global Future Council, 2018). Two historical agreements were thus adopted by the United Nations (UN), namely the 2015 Paris Agreement and the 2030 Agenda for Sustainable Development. Their objectives were to slow down the accelerated global warming and constrain the rise in temperature to below 2°C above pre-industrial levels and to ensure access to sustainable, affordable and reliable energy Sustainable Development Goal (SDG) 7 (Ram *et al.*, 2017). The goal of SDG-7 is intrinsically linked to other sustainable development goals, for example, poverty alleviation, quality education, good health and well-being (as shown in Figure 3.3), and is a critical enabler to achieve all sustainable development goals.

Figure 3.3 The linkage between SDG-7 (related to affordable and clean energy), and all other SDGs (Ram *et al.*, 2017)

Electricity has played a major role in the past and the demand for it will likely grow in the 21st century. In light of the current global climate change agenda to reduce the global carbon footprint, it is likely that the pace of electrification will increase, even though it is forecasted that the global energy demand will slow down as economies restructure their energy systems and improve efficiencies in the sector (World Economic Forum Global Future Council, 2018). However, the demand for electricity is predicted to increase in developing countries, especially those with low electrification rates, and countries with ageing electricity capacity (World Energy Council, 2014). Gas is also predicted to increase its global market share driven by the requirements to cut emissions and improve efficiencies (World Economic Forum Global Future Council, 2018). Oil will still play an important role in the near future, with forecasted stable demand due to a lack of alternatives in the transportation and petrochemicals sector (World Economic Forum Global Future Council, 2018). It is important to note that the current efforts towards higher quality energy sources, efficiency improvements and the rise in renewable energy sources are still not sufficient to meet the required cuts in the carbon emissions required to achieve the Paris agreement goals (World Economic Forum Global Future Council, 2018).

The energy sector accounts for two thirds of global greenhouse gas (GHG) emissions and will thus play an integral role in GHG reduction if it transitions from a fossil-fuelled energy to cleaner renewable energy (Ram *et al.*, 2017). Figure 3.4 shows that between 2010 and 2014, the global share of renewable energy generating capacity installed increased from 38% to 49%, contributing to the total renewable capacity almost doubling between 2007 to 2016 (Ram *et al.*, 2017). Ram *et al.* (2017) found that a future global energy system that is completely reliant on renewable energy by 2050 is possible to achieve and is technically and economically feasible. Ram *et al.* (2017) found that although solar and wind make up a large proportion of renewables currently used for electricity generation, a transition to 100% renewables will require the use of all types of renewables and electricity storage technologies for example, hydropower, geothermal, tidal energy, diverse batteries, power-to-gas, power-to-liquid and intelligent distribution systems. Ram *et al.* (2017) predicts that different regions will rely on different renewable sources based on the regional climatic conditions and that by 2050 coal, oil and gas power capacity will be used for strategic reserve only.

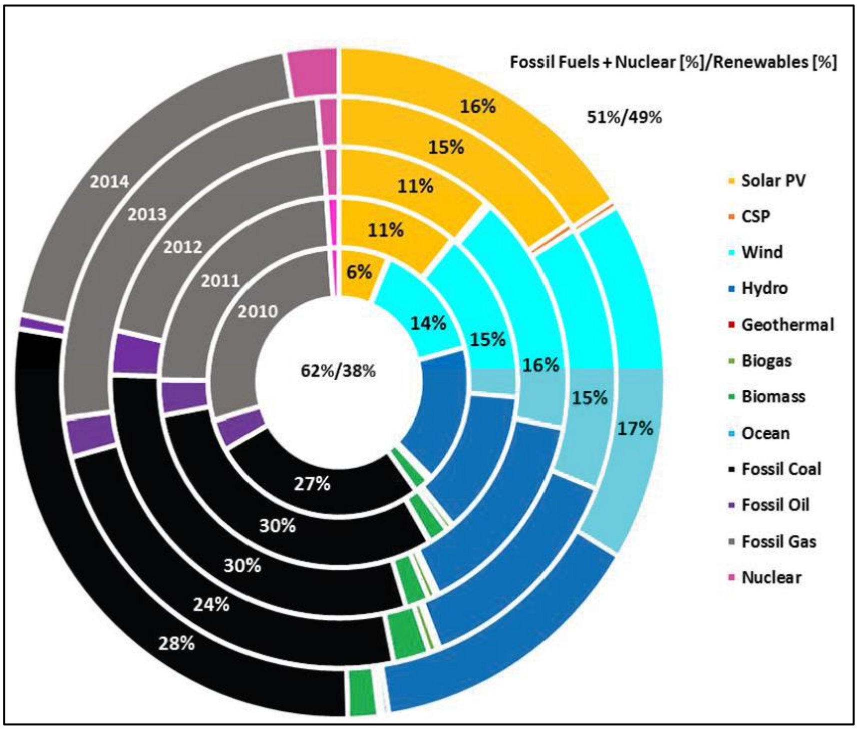

Figure 3.4 Annual power generation capacity installed globally from 2010 to 2014 (Ram *et al.*, 2017)

Organisations and global energy initiatives such as the International Energy Agency, Greenpeace, Royal Dutch Shell, World Energy Council and the World Wildlife Fund have also developed scenarios forecasting the future energy transition (Ram *et al.*, 2017). These models, shown in Figure 3.5, use variable assumptions, methodologies, targets and costs and result in a variable spread of predictions (Ram *et al.*, 2017). However, the overall trend that these models show is that the share of renewables will increase over the next 40 years and that the role of conventional sources of electricity as a percentage of the total generated capacity is set to decrease (Ram *et al.*, 2017).

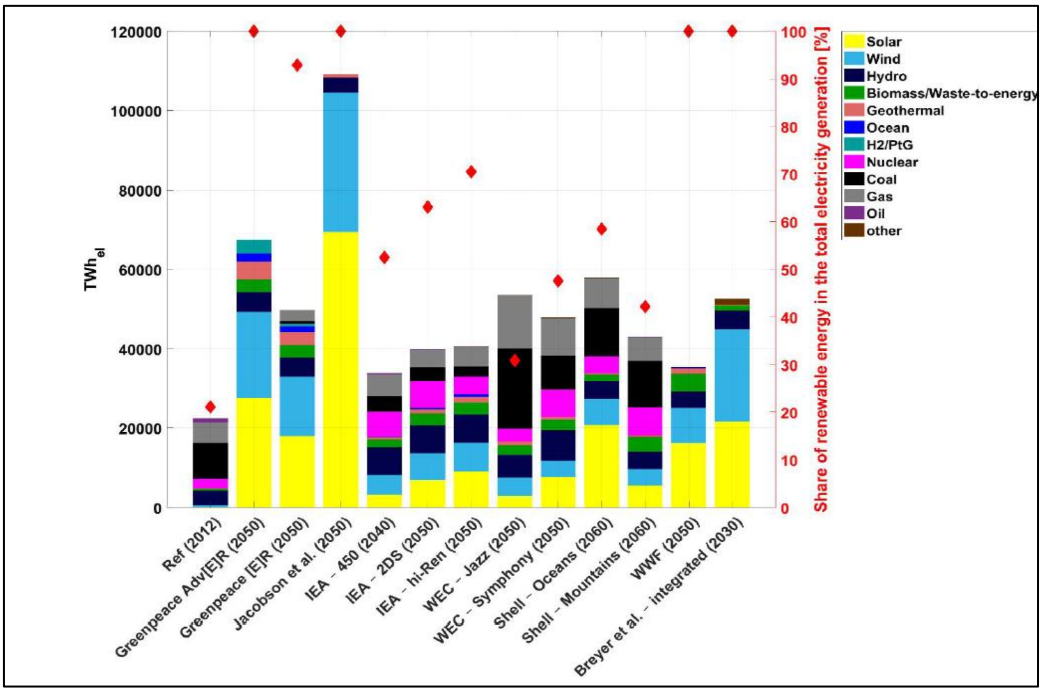

Figure 3.5 Various electricity generation predictive models for 2030, 2050 and 2060 plotted against a reference 2012 model (Ram *et al.*, 2017)

Whether or not a 100% transition to renewables is possible, many thought leaders globally acknowledge that any current energy transition will be fuelled by technology and innovation on a scale not seen before and difficult to predict (World Economic Forum Global Future Council, 2018). A number of factors affecting the energy industry, including decentralisation, innovation, shift in investment patterns, and changing market designs, can explain this unpredictability. Decentralisation of the energy systems, with innovative demand side management solutions is altering the energy landscape by turning yesterday's consumers into contributors, allowing the markets to shape the energy system design (World Economic Forum Global Future Council, 2018; World Energy Council, 2018). This is an on-going process with many newcomers to the energy market every year, thus making their impact difficult to predict (World Economic Forum Global Future Council, 2018). Innovations in generation, demand management and storage solutions have been responsible for higher market penetration of renewable technologies, such as wind and solar (World Economic

Forum Global Future Council, 2018). The energy sector's capital-intensive expansion has largely slowed over the last few years due to uncertainty surrounding the recovery of these long-term investments (World Economic Forum Global Future Council, 2018). Additionally, changing market designs have driven the rise of cost-efficient renewable power generation, storage and peer-to-peer distribution (which can sometimes reduce government's capability to control and tax the energy sector) (World Economic Forum Global Future Council, 2018).

Decentralisation of the energy systems is already taking place and it refers to the process of shifting away from the centrally generated and distributed power to power generated on much smaller scale. This becomes a viable case when it comes to providing power to remote areas and communities, in the form of micro-grids or solar-powered individual systems, instead of costly traditional links to the centralised grids (World Economic Forum Global Future Council, 2018). There is however also great uncertainty and divergent academic views on the future energy demand, in particular oil and electricity, the role that consumers will play in transitioning the energy system, the future transportation systems, disruptions introduced by innovative technologies, the future nature of work and the future power utilities (World Economic Forum Global Future Council, 2018).

3.1.3 Energy challenges

Energy transition, in particular a shift in the energy towards decentralisation, digitalisation, and decarbonisation has been identified as one of the main challenges faced by the energy sector (World Energy Council, 2018). The World Energy Council (2018) provided key insights and a tool for understanding the critical global and regional issues, uncertainties and complexities within the energy transition landscape through its World Energy Issues Monitor. Figure 3.6 shows the Global Issues Map, which was produced from over 1200 responses from ministers and industry and resulted in over 30 country assessments across six regions (World Energy Council, 2018). The role of decentralised energy generation continues to grow with innovative demand-side management solutions altering the energy landscape by turning yesterday's consumers into contributors, allowing the markets to shape the energy system design (World Energy Council, 2018). Innovation and the rising role of renewable energy have a greater impact on energy transition and diversification of energy supply (World Energy Council, 2018). Globally, there is greater certainty around issues such as electricity prices and energy affordability than the digitalisation, Internet of Things (IOT), Blockchain and data Artificial Intelligence issues (World Energy Council, 2018).

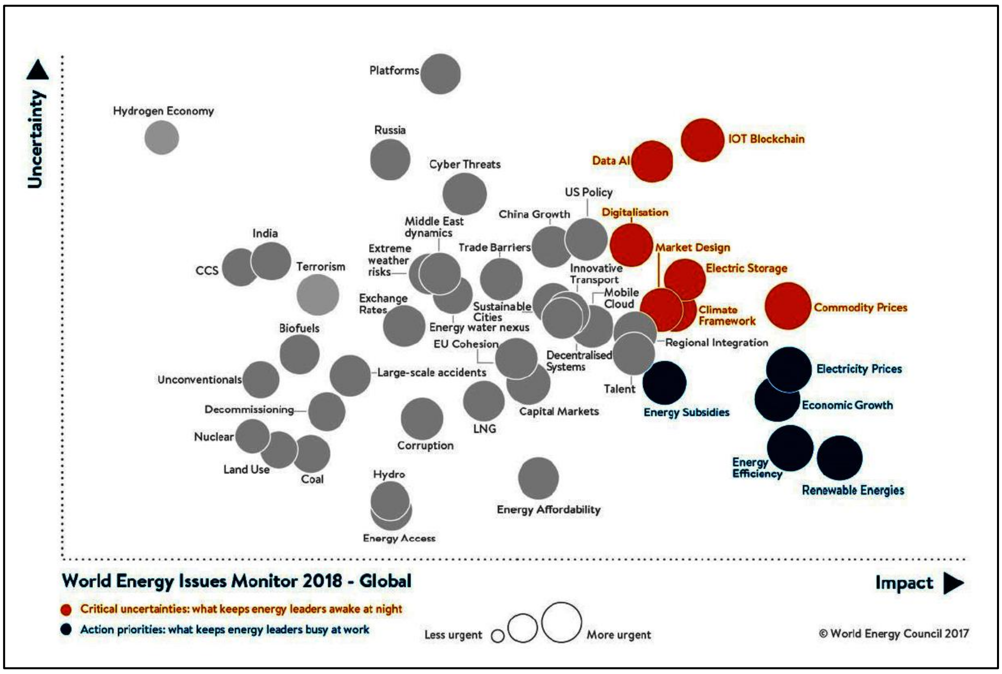

Figure 3.6 The global view on issues related to energy transition (World Energy Council, 2018)

Furthermore, the World Energy Council (2018) states that it is imperative to strike a balance between energy equity, environmental sustainability and energy security to ensure a timely, well managed and global energy transition and to ensure the sustainability of the energy sector and to drive sustained economic growth in individual countries. The council therefore analysed the global energy issues through the lens of energy equity, energy security and environmental sustainability to produce the Global Energy Issues Map in Figure 3.7. It is evident that the energy equity issues encompass affordability, energy access and subsidies as well as electricity prices. These issues have high certainty and variable impacts and it is believed that technological advancements and decentralisation could address most of these issues (World Energy Council, 2018). Energy security issues are framed in the context of new technologies designed to improve energy efficiency and increase coverage of renewable energy, leading to changing market design, cyber threats and digitalisation. Because of the high technological component, these issues have a high uncertainty (World Energy Council, 2018). The environmental sustainability factor has been a major driver of energy efficiency and renewable technologies, supported by overall diversification from primary energy sources, with many countries adding 'green' energy to their energy mix (World Energy Council, 2018).

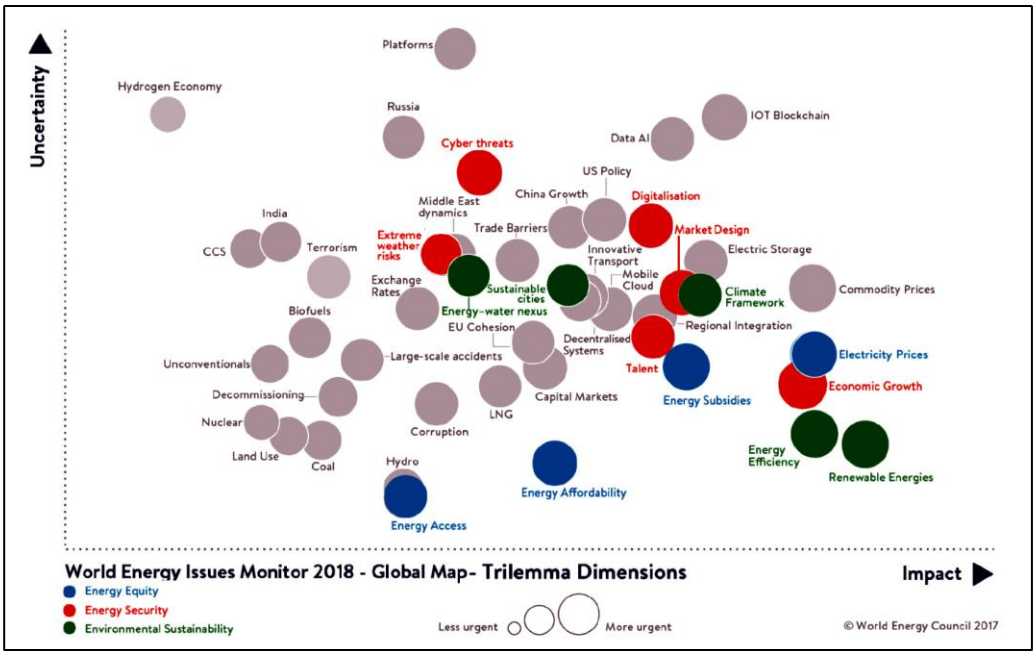

Figure 3.7 Key global energy challenges and a categorisation of some challenges into energy equity, energy security and environmental sustainability (Energy Trilemma) (World Energy Council, 2018)

Figure 3.8 shows the most pertinent issues with the greatest uncertainty for South Africa, namely (World Energy Council, 2018):

a) Commodity prices - South Africa's economy is closely linked to mining and commodity prices are unpredictable;

b) The energy water nexus - South Africa's energy generation is largely dependent on wet cooled power plants;

c) Market design - the South African government is under pressure to restructure the monopoly of the national power utility and give independent power producers direct access; and

d) Electric storage (especially when adding renewable energy generation to the mix).

Other issues relevant to South Africa include low economic growth, rapidly increasing electricity prices against the backdrop of reducing demand and increasing the share of renewables in the energy mix (World Energy Council, 2018).

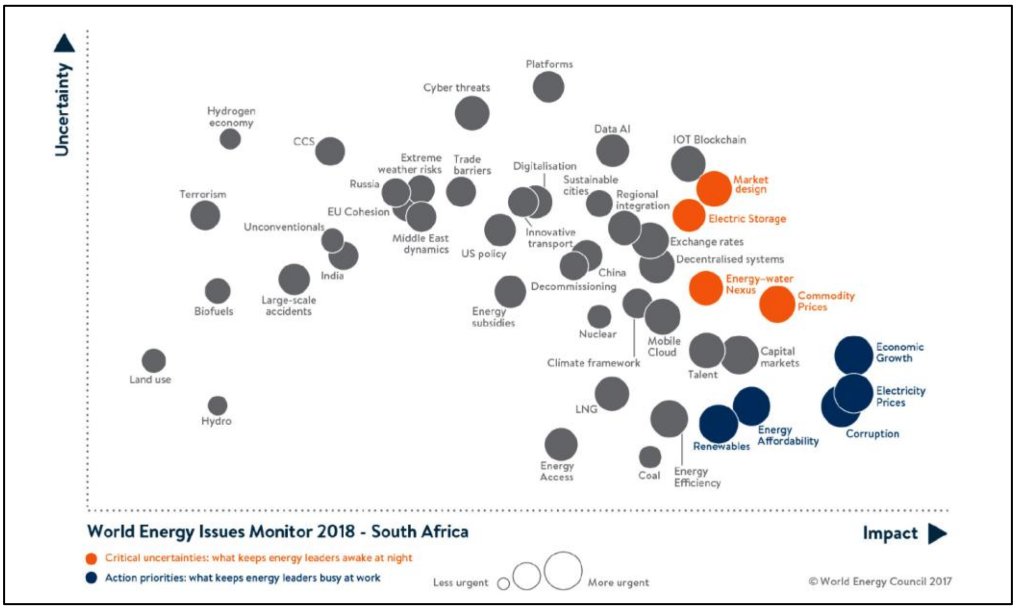

Figure 3.8 Critical energy issues and priorities for South Africa (World Energy Council, 2018)

3.2 Water

Water is critical for life and is a primary input across a wide range of economic activities. Due to the abundance of water covering most of the Earth's surface area, it is often named the Blue Planet. However, less than 3% of this water is fresh (Hinrichsen and Tacio, 2002). One of the major global water challenges in this century is access to freshwater of sufficient quality required for human consumption (Distefano and Kelly, 2017). There is great spatial variability in water distribution, leading to water-scarce and water-rich regions (Cosgrove and Loucks, 2015). This unequal distribution of freshwater results in some regions having insufficient freshwater to meet human and economic development needs (Cosgrove and Loucks, 2015). The Global Water Report 2018 by the World Economic Forum ranks water risks amongst the top five risks with the highest societal impact over the next decade, making water one of the highest priority areas for governments, businesses and societies globally (World Economic Forum, 2017; World Economic Forum, 2018).

Geography, climatic conditions and socio-economic circumstances dictates the regional variations in freshwater availability across the globe (Distefano and Kelly, 2017; World Economic Forum, 2017; Proskuryakova *et al.*, 2018). Climate change further exacerbates the already unequal distribution and limited availability of freshwater through increased evaporation rates, thereby intensifying droughts in already water-scarce regions and increasing floods in wet regions (Rábago *et al.*, 2001; Ranchod *et al.*, 2015; Distefano and Kelly, 2017; Proskuryakova *et al.*, 2018). Extreme weather events such as flooding and droughts are associated with large financial costs and have a negative impact on the affected population. According to the World Health Organisation, approximately two billion people were victims of natural disasters between 1997 and 2007, most of which were flood and drought events (Cosgrove and Loucks, 2015). Droughts, however, pose a long-term problem compared to short term flooding events and are the greatest threat from climate change (World Water Assessment Programme/ United Nations Water, 2018).

For centuries, water played a foundational role in the rise and fall of civilisations, giving rise to conflict over control of and access to water resources, which is often interlinked with a broader spectrum of political, ideological, religious, cultural and economic factors (Adler *et al.*, 2007; De Lange, 2016). Unlike other commodities, water is not traded, because of the associated transport costs of this undervalued resource and the overall resistance to the commodification of water since it is a basic human right (Cosgrove and Loucks, 2015). The international transfer of water mostly occurs via natural flow systems and in rare cases by transportation and is often governed by international politics as opposed to trade agreements (Cosgrove and Loucks, 2015). The inherent mobility, open access and common property of water (De Lange, 2016) could lead to potential "water wars". Examples of current areas of potential conflict include the Nile river leading to increased tensions between Egypt, Sudan and Ethiopia, the Indus in south east Asia, the Dead Sea between Israel and Jordan and the Jordan river (Engelke and Sticklor, 2015). Closer to home, Likoti (2007) insinuates that South Africa's involvement in a peacekeeping intervention in neighbouring country Lesotho in 1998, was shrouded in controversy due to the absence of legal grounds and was linked to the protection of South Africa's access to water resources in Lesotho.

3.2.1 Water scarcity

Half a billion people are already affected by water scarcity throughout the entire year whilst a third of the world population are affected by water scarcity for at least one month in the year (Distefano and Kelly, 2017). Figure 3.9 shows the global water scarcity in 2010 and the forecasted change in water scarcity between 2010 and 2050 (World Water Assessment Programme/ United Nations Water, 2018). In Figure 3.9, areas are classified as water-scarce if the total annual withdrawal for human consumption is between 20% and 40% and regions with withdrawals greater than 40% classified as severely water-scarce (World Water Assessment Programme/ United Nations Water, 2018). Figure 3.9 also shows that the already water-scarce regions are projected to experience severe water scarcity by 2050, resulting in a greater number of people affected by the scarcity (Distefano and Kelly, 2017; World Water Assessment Programme/ United Nations Water, 2018). Distefano and Kelly (2017) further found that the impact of water scarcity would vary based on region and the stage of economic development. Through numerical simulations, the study showed that GDP growth is the most important driver of water scarcity, followed by the uncertainty of climate change, which greatly affects water-stressed regions (Distefano and Kelly, 2017). Thus, it is important to note that water challenges are unique to regions and countries, making the formulation of a global response difficult (Addams *et al.*, 2009).

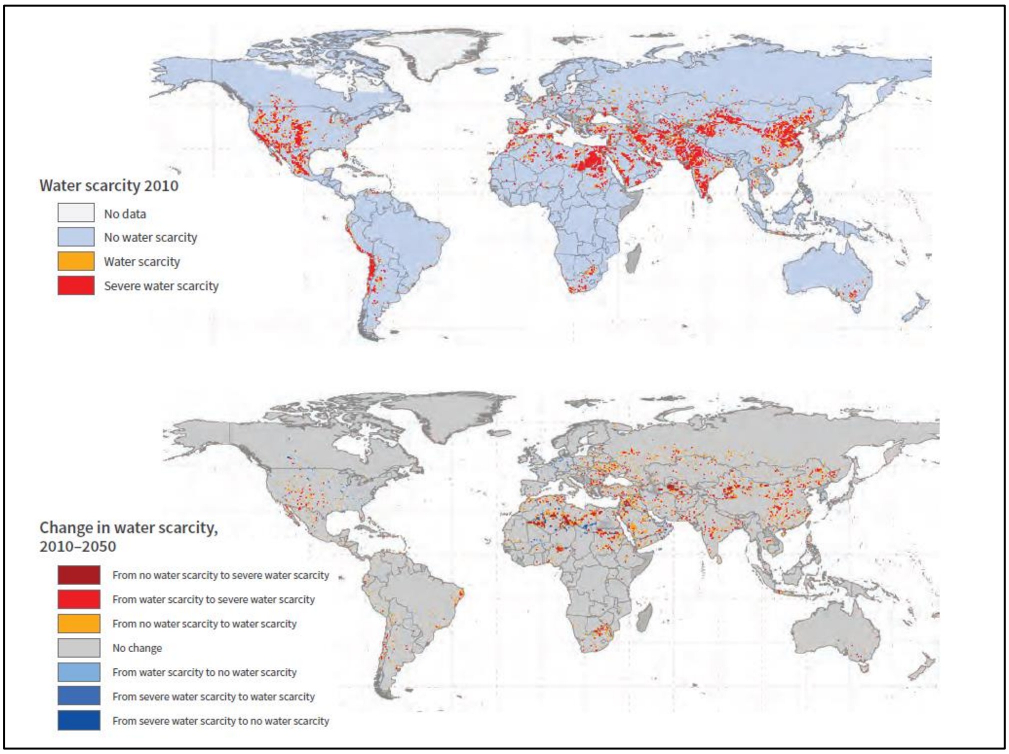

Figure 3.9 Top map - Water scarce regions in 2010; Bottom map - Projected change in water scarcity between 2010 and 2050 (Distefano and Kelly, 2017)

Water scarcity is forecasted to increase in the coming century with far-reaching consequences for both society and ecosystems and will potentially negatively impact key policy goals in the modern world such as food security, economic growth and environmental sustainability (Distefano and Kelly, 2017; Proskuryakova *et al.*, 2018). Water scarcity poses a significant challenge to sustained economic growth in both developed and developing countries (Distefano and Kelly, 2017). The current global efforts aimed at tackling water scarcity are mainly aimed at developing policies designed to alter water use patterns, promote sustainability of the water sector and reduce the water footprint of economic activity (Proskuryakova *et al.*, 2018). One of the major concerns for all water users relates to the management of ground water and reservoir systems in an environment impacted by climate change (Lettenmaier *et al.*, 1999). With the increased uncertainty and speed at which climate change is affecting weather patterns, the use of just historical data may not be adequate for water infrastructure planning (Cosgrove and Loucks, 2015). Improved and more thorough water infrastructure is required that consider, and are adaptable to include, the potential of more frequent extreme weather events (Cosgrove and Loucks, 2015). Global climate modelling research is quite advanced, but local models that affect water infrastructure planning such as precipitation models need further research (Cosgrove and Loucks, 2015).

3.2.2 Water demand

Global freshwater consumption increased six-fold over the last century and continues to grow at a rate of approximately 1% per year (World Water Assessment Programme/ United Nations Water, 2018). According to the 2030 Water Resource Group, maintaining the status quo would likely result in a 40% water deficit (World Economic Forum, 2017). This increased water consumption is largely attributed to a growing population and its associated economic activities (including energy, industrial and manufacturing), rapid urbanisation, globalisation and agricultural activities (Cosgrove and Loucks, 2015; World Water Assessment Programme/ United Nations Water, 2018).

The global population is forecasted to grow from 7.7 billion in 2017 to approximately 10 billion by 2050 (Cosgrove and Loucks, 2015; World Water Assessment Programme/ United Nations Water, 2018). This implies that the additional 2.3 billion people will require access to food, water and energy in excess of the currently unsatisfied needs of at least one billion people (Cosgrove and Loucks, 2015). Interconnectivity of the above-mentioned needs through their interdependencies and feedbacks will require novel integrated management (Cosgrove and Loucks, 2015). Future water demand is projected to increase by 20 to 30% over the next 30 years, which falls in line with part demand growth trajectory and implies further strain on an already constrained freshwater supply

(United Nations Water Decade Programme on Advocacy and Communication, 2011; World Water Assessment Programme/ United Nations Water, 2018).

Globally, the agricultural sector is the largest water user and accounts for approximately 70% of freshwater withdrawals, mostly from groundwater for irrigation purposes. Driven by population growth and the requirement to expand food production, most of the water demand will come from the agricultural sector (World Economic Forum, 2017; World Water Assessment Programme/ United Nations Water, 2018). Domestic water consumption accounts for approximately 10% of the freshwater withdrawals and is forecasted to increase due to rapidly growing urban populations (World Water Assessment Programme/ United Nations Water, 2018).

Driven by economic growth in developing nations, industrial activity that currently accounts for approximately 20% of global freshwater demand, is forecasted to grow many-fold and with it the requirement for more water to sustain industrial growth (United Nations Water Decade Programme on Advocacy and Communication, 2011; World Water Assessment Programme/ United Nations Water, 2018). Manufacturing is predicted to increase by 400% and the energy sector by 20% by 2050 (World Economic Forum, 2017). Every economically successful nation that managed to tackle poverty has done so by investing in the basic building blocks such as energy, transport, food security and water (Cosgrove and Loucks, 2015). In most industries, especially process industries, water is one of the largest input resources, yet it is frequently undervalued economically, with insufficient importance placed on proper industrial water management (Wintgens *et al.*, 2013). Globalisation and the international trade of products that have high water consumption embedded in their production processes (termed virtual water) also have a negative impact on local water systems (Cosgrove and Loucks, 2015). The short-term trade gains achieved from goods produced with high embedded water content are not sustainable, especially in water-stressed countries (Cosgrove and Loucks, 2015). Countries should also align their trade policies to sustainable water goals, paying particular attention to embedded water in low value goods (Cosgrove and Loucks, 2015).

Industry is also one of the largest polluters of water resources, often discharging untreated waste into water, thus contaminating and further reducing freshwater availability (United Nations Water Decade Programme on Advocacy and Communication, 2011; Wintgens *et al.*, 2013). This contamination leads to environmental degradation and has a negative impact on the sustainability of freshwater supply for other water users (United Nations Water Decade Programme on Advocacy and Communication, 2011). Other modifications to our water systems caused by human activity include changes in river flows, large variability in precipitation patterns, over-utilised groundwater resources, water pollution and the amount and timing of rainwater runoff (Cosgrove and Loucks, 2015). Most ecosystems have a major impact on water availability, quality and associated water risks (World Water Assessment Programme/ United Nations Water, 2018). The study found that trends in ecosystem changes such as land use change, soil degradation and erosion, loss of wetland areas and deforestation increase the risk of natural and climate-associated disasters, even though it is difficult to quantify (World Water Assessment Programme/ United Nations Water, 2018). However, reversing these ecosystem degradation trends and focusing on ecosystem management, restoration and conservation could contribute positively towards water resource management challenges and availability risk (World Water Assessment Programme/ United Nations Water, 2018).

These trends in overconsumption of freshwater will not be offset with water efficiency gains from technological advances (Addams *et al.*, 2009; Distefano and Kelly, 2017). Addams *et al.* (2009) showed that historical annual efficiency gains from 1990 was 1%, which is forecasted to be 20% by 2030. As shown in Figure 3.10, these efficiency gains, however, are not enough to offset the remaining demand gap in 2030 under a business-as-usual scenario and will leave a substantial gap of 60% (Addams *et al.*, 2009). Addams *et al.* (2009) noted that the business-as-usual scenario could result in two possible outcomes, namely tapping into water from environmentally sensitive areas or not closing the gap, resulting in social and economic issues.

Greater effort is required to reduce consumption and the business-as-usual scenario. The biggest gains could be achieved if the global society at large moves towards the sustainable practices and behaviour aimed at conserving and using water in the most efficient way. This will require a shift towards more unconventional thinking and investment in water-related infrastructure (Cosgrove and Loucks, 2015).

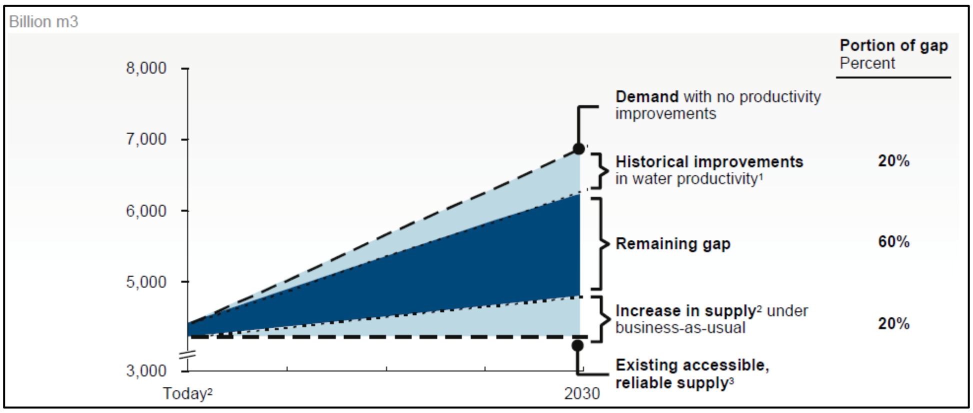

Figure 3.10 Projected water demand volumes between 2010 and 2030 (Addams *et al.*, 2009)

3.2.3 Global water initiatives and water governance

The end of the World War 2 ushered in a new era of collaborative solutions and approaches towards multinational issues that have broad regional impacts (Varady, 2004). Water was identified as one of the key issues to be addressed on a global scale since it not only is a key resource to human wellbeing, but it cuts across national borders and its careful management requires coordinated efforts to ensure equitable access based on the sound scientific approaches (Varady, 2004; Varady *et al.*, 2009). This transformation of viewing water through a global lens is largely due to a systematic adoption of global governance frameworks (Varady *et al.*, 2009). Further driven by population growth and increasing fear of international water conflicts, various international bodies that formed the building blocks of the various water initiatives became active in the international water conservation, policy and management space (Varady, 2004).

The largest and most well-known global water initiatives are World Water Council (WWC), Global Water Partnership (GWP), Global International Water Assessment (GIWA) and World Water Assessment Programme (WWAP) (Varady, 2004). The first two initiatives, WWC and GWP, which are activists in their nature, have the most modern approaches and have mapped the most comprehensive plans to improve access to water, enhance water security and reduce poverty (Varady, 2004). The other two, GIWA and WWAP, are mostly focused on mapping the state world water resources as well as providing scientific input and guidance into formulation of water policies. These initiatives are often associated with other international food and health programmes due to established linkages between them (for example, food security, agriculture and access to water or public health and access to water) (Varady, 2004). Besides the above-mentioned initiatives, there are many others with international and regional footprints, focused on improving scientific knowledge and building international cooperation (Varady, 2004). Most of the above-mentioned global water initiatives have a proven record of accomplishment in improving understanding of the global water issues, in gathering data, which formed the basis of many scientific studies, and in improving international and regional cooperation and dialogue on key water challenges (Varady, 2004). Some of the Global Water Initiatives (GWIs) are broad focused, others are more narrow focused and the focus of some GWIs has occasionally overlapped (Varady, 2004).

Varady (2004) developed an initial model illustrating the evolution of global water initiatives over the past 50 years, presented in Table 3.1. According to Varady (2004), the different GWIs have certainly made a positive impact and shown some successes in terms of reducing interdisciplinary and global communication barriers, gathering and analysing water-related data, the development of water management techniques and technologies and enhancing public participation in addressing water challenges (Varady, 2004). However, until the tools to quantify the impact of these water initiatives are developed, it is not possible to accurately gauge the successes of these initiatives (Varady, 2004).

Table 3.1 Model of the evolution of global initiatives over the last 50 years

Started as	Evolved to
Professional concerns and desire to improve science, understanding and communication.	Multilateral efforts to address water issues on a global scale.
Aggregated attempts to consider global water problems.	Specific sectoral thematic and issue-oriented approaches.
Understanding that water is an important resource.	Recognition that access to potable water and sewage is key to development and poverty reduction.
Impulse to move beyond data acquisition and theory.	Determination to improve on-the-ground conditions via tailored programmes.
Desire to harness science and technology in order to effect change.	Definition of ambitious, progressive, action-oriented agendas.
Large multi-objective programmes and approaches with over-arching goals.	Smaller tailored programmes that focus on characteristics and procedures that make water management more efficient, responsive, equitable and conflict-reductive.

Source: Varady (2004)

United Nations Water (UN-Water) is an inter-agency mechanism established in 2003 to coordinate actions required to meet the UN Millennium development goals related to water and to implement the decisions taken on the water-related challenges tabled at the 2002 World Summit on Sustainable Development (Baumgartner and Pahl-Wostl, 2013). The UN-Water also monitors progress on the 2030 Agenda for Sustainable Development - Sustainable Development Goal 6 (SDG6) which is an expansion of the UN Millennium development water-related goals and encompasses “the availability and sustainable management of water and sanitation for all” (World Health Organization and UN-Habitat, 2018, p. 7). UN-Water mainly operates in the procedural aspects of the Global Water Governance system, namely legitimacy, accountability, awareness etc. (Baumgartner and Pahl-Wostl, 2013). According to the United Nations Development Plan, water governance encompasses a variety of administrative, social, political and economic frameworks that underpin the management of available water resources and the provision of water to society (Baumgartner and Pahl-Wostl, 2013). Globally, these frameworks include the setting of water quality standards, formulating water policies and the co-ordination of available resources (Baumgartner and Pahl-Wostl, 2013). Additionally, a systems approach to water governance is required by considering linkages between different levels of water policy spectrum (local to global) and water challenges cannot be addressed in isolation without considering interdependencies between water and other sectors such as energy, agriculture and industry (Baumgartner and Pahl-Wostl, 2013).

The 2030 Water Resource Group was established by the World Economic Forum's Global Water Initiative and is designed to shape reforms and water policies in developing countries by establishing partnerships between the business sector and governments as well as providing input into water management and conservation projects (World Economic Forum, 2017). The Fourth Industrial Revolution will likely shape the future water initiatives and programmes with associated advances in machine learning and artificial intelligence assisting with analysing both historical and real-time data in order to improve water management, increase water efficiencies and create business opportunities (World Economic Forum, 2017).

The Carbon Disclosure Project (CDP) is a global non-profit organisation that drives environmental reporting of major companies, striving for disclosure, accountability and action in support of environmental risk mitigation (Carbon Disclosure Project Worldwide, 2017). The CDP launched its water disclosure concept in 2009, focused on encouraging companies to measure and disclose their annual water information, towards greater transparency and accountability (Carbon Disclosure Project Worldwide, 2017). The data collected by the CDP is used by investors to make informed financial decisions and to foster a business environment that links water resources and financial information (Carbon Disclosure Project Worldwide, 2017). From 2009 to 2017, the number of investors on the platform has grown from 137 to 639 and the number of companies volunteering their water data has grown from 175 to 742 (Carbon Disclosure

Project Worldwide, 2017). The CDP compiles the water-related data into an annual report aimed at highlighting industry actions towards sustainable use of water resources and the identification of water risks that could potentially stunt industrial sustainability (Carbon Disclosure Project Worldwide, 2017).

The increase in water scarcity will result in prominent business and economic risk, especially for businesses whose value chains rely on secure water supplies (Addams *et al.*, 2009). Businesses could play an active role and be a positive force for change by sharing data and participating in the various global initiatives that strive to understand the nature of the problem and table potential solutions (Addams *et al.*, 2009). The ultimate goal is to have a systematic framework that could be applied on a country and watershed level to understand the economic value of water as well as benchmarking potential solutions (Addams *et al.*, 2009). It is also important to financially incentivise water management and efficiency interventions at all levels, for example, individual, local and regional levels (Cosgrove and Loucks, 2015).

Addams *et al.* (2009) suggested several solutions for countries to manage their way through water scarcity, some of which are summarised below:

a) An integrated approach for water sector transformation will require building capacity and momentum, working closely with stakeholders and improving regulations and strengthening water institutions;
b) The market design and economic interventions will require a modification of the water pricing model to ensure that water is assigned a true economic value and the involvement of the private sector in the water market, for example, countries with informal water sectors can make use of subsidies to encourage water conservation;
c) Transforming water institutions on a country level through improving governance, reducing political interference, increasing funding and improving overall management;

d) Getting the private sector on board through capital provision, water user and a solutions provider. Leveraging private sector investment in the water sector will require clear government plans and incentives;
e) Encourage water efficiency practices by large water users beyond agriculture, for example, mining and manufacturing through policies; and
f) Capitalise water research, education and technology centres to drive future innovations and research in the water sector.

The duration and severity of droughts can be managed by increased water storage in drought-prone regions (World Water Assessment Programme/ United Nations Water, 2018). The water storage will require conventional infrastructure investments and increased diffusion of green technologies and solutions (World Water Assessment Programme/ United Nations Water, 2018).

3.3 The Water-Energy Nexus

As shown in this chapter, it is evident that both water and energy are important for life and sustained economic growth. Water and energy are also interconnected as access to water relies on the availability of energy and the production of energy is reliant on the availability of water (World Bank, 2017). Water is required for energy production, for example, for hydropower, cooling of thermal power plants and nuclear reactors. In turn, energy is required to transport water from surface and underground reservoirs and for the desalination of water. This interconnectivity implies that both sectors would benefit from integrated management, especially in relation to policies and regulations that focus on the linkages between the two sectors (Cosgrove and Loucks, 2015; World Bank, 2017). As the demand for water grows, the demand for energy also grows to facilitate the transfer of water from greater distances and depth, desalination and rehabilitation of grey water discharge from industry (World Bank, 2017). Desalination is a much more expensive solution compared to conventional water supply infrastructure (Addams *et al.*, 2009). The reliance on carbon-intensive energy options represents a downward spiralling effect since greenhouse emissions potentially further accelerate climate change and water scarcity (World

Bank, 2017). A current concern is that the global energy crisis currently being experienced will be followed by a global water crisis (Cosgrove and Loucks, 2015).

3.4 Conclusion

Both water and energy are major global challenges and are ranked amongst the top business risks. Access to energy, especially electricity, underpins economic, industrial and social aspirations of all countries and drives the production of goods and delivery of services. Energy demand has however increased drastically over the last 20 years, driven by population and economic growth. Hydrocarbon-based fuels dominate the global energy supply and are the largest contributor towards GHG emissions. Recent efforts in this sector focused on introducing renewable energy into the mix in order to reduce GHG emissions. This effort is driven by the 2015 Paris agreement aimed at slowing down the rate of global warming. This decarbonisation effort coupled with digitalisation and decentralisation of the sector are key global energy challenges.

Water is unequally distributed throughout the world and geography, climatic conditions and socio-economic circumstances will dictate freshwater availability in different regions. The accelerated pace of climate change driven by the current dominance of carbon-intensive energy sources further exacerbates the already limited availability and geographically unequal spread of fresh water. Future water demand is projected to grow and outstrip available water supply over the next 30 years, especially in water-scarce regions. This increasing water demand will largely be driven by population growth and increased economic activity, which includes expansion of agriculture, manufacturing, industry and energy sectors. Current global efforts are focused on addressing water scarcity by developing policies aimed at changing consumption patterns, improving the sustainability of the water sector and reducing the water footprint of economic activity. Formal water initiatives form the building blocks of the global efforts aimed at global water conservation policy and management. Water and energy are interdependent and would thus benefit from integrated management.

4 THE SOUTH AFRICAN ENERGY LANDSCAPE

4.1 Introduction

In South Africa, energy represents a strategic and critical resource that forms a cornerstone of its economic and industrial developmental aspirations (Motiang and Nembahe, 2017). The birth of the mining industry in South Africa and the availability of an abundant supply of inexpensive coal sparked the development of a vibrant inexpensive electricity industry (Ting, 2015; Montmasson-Clair, 2016). Figure 4.1 shows that in 2015 coal dominated the primary energy supply of South Africa by 59%, followed by 20% renewable energy sources and 16% crude oil, with natural gas and nuclear jointly accounting for 5% (Ratshomo and Nembahe, 2018). South Africa relies mostly on coal for electricity generation with 90% of its electricity capacity derived from coal-fired power plants, resulting in a major market for the local coal mining industry (Johnson and Fourie, 2012; Montmasson-Clair, 2016). In addition to electricity generation, 30% of synthetic liquid fuels are also derived from coal (Ting, 2015).

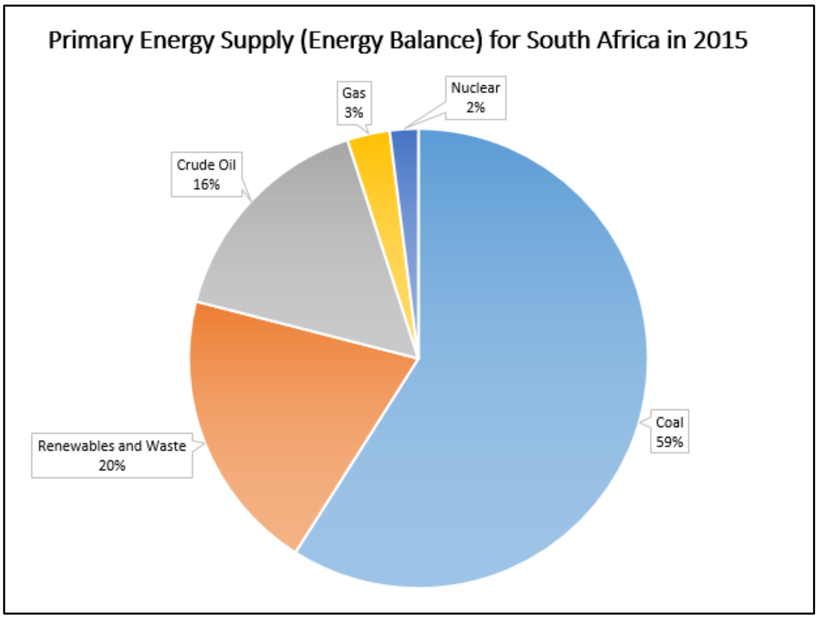

Figure 4.1 South Africa's energy balance for 2015 (Adapted from Ratshomo and Nembahe (2018))

ESKOM (South Africa's national power utility) dominates the electricity sector in South Africa, generating and supplying 95% of the country's electricity needs, with the remainder supplied by various independent power producers (IPPs), municipalities and smaller distributors (Motiang and Nembahe, 2017). ESKOM is one of the largest power utilities globally and was ranked in the top 15 by generation capacity in 2008 (Ting, 2015). ESKOM employs a two-tier approach to tariff allocation, whereby the first-tier customers are large industrial users and second-tier customers are municipalities (Ting, 2015).

South Africa's fossil fuel (coal and hydrocarbons) based energy sector accounts for more than 70% of its GHG emissions (0.743 kg of CO_2 per purchasing power parity US$ of GDP in 2011) making it one of the most carbon intensive economies in the world (as shown in the graph in Figure 4.2) (Ting, 2015; Montmasson-Clair, 2016). In 2015, South Africa ratified the Paris climate change agreement in response to the global need to address the consequences of climate change (Montmasson-Clair, 2016). South Africa pledged to firstly reduce its GHG emissions to 34% below business-as-usual emissions trajectory by 2020 and 42% below business-as-usual emissions trajectory by 2025. Thereafter it will keep GHG emissions constant up to 2035 and finally reduce it by a finite amount to be defined, subject to financial, technological and capacity building support provided by developed nations (Montmasson-Clair, 2016).

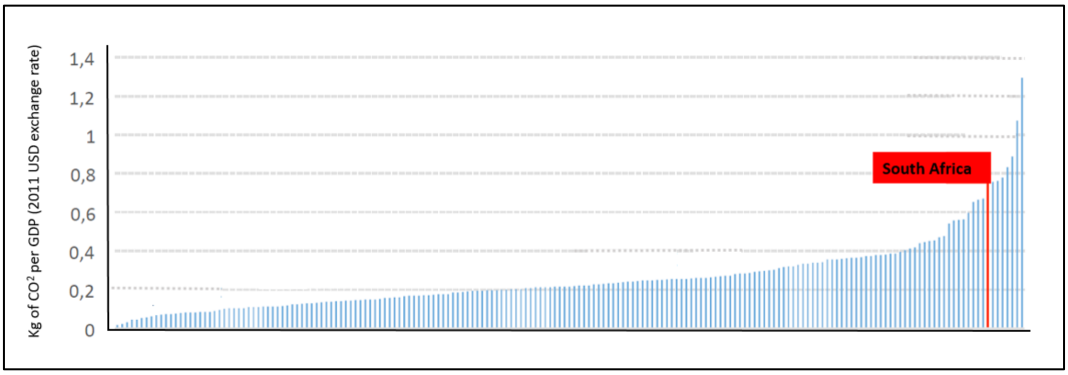

Figure 4.2 South Africa's global ranking with regards to carbon intensity (measured in Kg of CO^2 per unit of GDP) (Montmasson-Clair, 2016)

In aiming to meet its growing electricity demand, estimated at 6% year-on-year (Tshisekedi, 2009), ESKOM is currently augmenting its existing national supply capacity with two additional coal-fired power stations, Medupi and Kusile, with more coal-fired power stations in the pipeline (Ting, 2015). South Africa started levying a carbon tax since June 2019. In order to fund the reduction of its carbon footprint and facilitate a change in consumer behaviour, a tax levy of R120 per tonne of CO_2 emitted at the source is charged if a reduction of 40% in emissions is not achieved (Visser, 2017).

4.2 Energy and Mining in South Africa

The South African industrial electricity prices have provided its mining sector with a competitive advantage of low-cost electricity, with some of the lowest electricity prices globally (LTE Energy in association with EA Energy Analysis, 2012; Thopil and Pouris, 2013; Du Plessis *et al.*, 2014; Motiang and Nembahe, 2017). Table 4.1 compares household and industrial electricity prices of a few countries including South Africa (Thopil and Pouris, 2013). Thopil and Pouris (2013) showed that globally, industrial tariffs are approximately 30% cheaper than domestic tariffs; however, for South Africa, industrial tariffs are over 60% cheaper. These low electricity prices not only enabled the South African mining industry’s existence but sustained profitability. In some industries, such as iron ore, it enabled the creation of beneficiation capacity.

South Africa’s electricity sector has seen a dramatic price increase since the 2008 financial and electricity crisis spread across all sectors (Motiang and Nembahe, 2017). The infographic in Figure 4.3 illustrates that between 2007 and 2015 electricity tariffs increased by 300.7%, whereas inflation for the same period increased by 45.1%. This dramatic increase was unplanned and eroded profitability and international competitiveness of many mining companies (Moolman, 2017). Underinvestment in energy capacity and infrastructure expansion culminated in the electricity supply bottleneck, which was further exacerbated by increasing residential energy demand, resulting in South Africa’s loss of competitive advantage as a low-cost energy destination for mining related projects (Ernst and Young Global Limited, 2014). Between 2007 and 2012 the platinum mining sector witnessed a 238% electricity price increase, which represents a major risk for sustainability and profitability of the sector going forward (Ryan, 2014).

Table 4.1 A comparison of domestic and industrial electricity tariffs for various countries (in US$ cents/kWh and adjusted for purchasing power parity)

Country	2007		2008		2009		2010	
	Domestic	Industrial	Domestic	Industrial	Domestic	Industrial	Domestic	Industrial
Belgium	14.51	9.62	18.53	9.83	16.05	11.39	16.85	10.87
Denmark	12.65	9.42	16.95	11.34	14.89	10.52	15.54	11.24
France	10.35	5.82	10.25	6.33	10.34	6.73	11.29	7.11
Finland	9.23	5.98	10.38	7.03	10.63	7.2	11.18	7.16
Greece	12.53	10.98	15.05	13.12	13.25	12	13.27	12.12
Ireland	17.64	12.89	18.85	14.93	18.1	12.95	18.83	12.99
Mexico	13.06	14.45	13.39	15.82	10.68	11.78		
Netherlands	15.05	10.03	15.61	10.52	16.34	10.92	15.1	10.12
Norway	13.17	7.73	15.85	9.58	14.91	8.87	17.99	10.38
Spain	15.82	12.52	17.75	14.12	19.4	15.59	20.75	14.46
South Africa	9.95	3.81	9.97	3.86	11.25	4.56	12.81	5.41
South Korea	11.49	8.44	14.09	9.93	9.67	7.43		
Sweden	12.48	8.02	14.57	9.84	14.05	9.07	16.59	10.83
Switzerland	9.66	5.93	10.34	6.32	9.82	5.87		
Taiwan	11.93	9.23	12.48	9.49	12.82	11.73		
UK	17.38	12.72	19.61	13.45	17.78	12.91	17.89	12.42
USA	10.06	6.17	10.34	6.44	11.05	6.87		

Source: Adapted from Thopil and Pouris (2013)

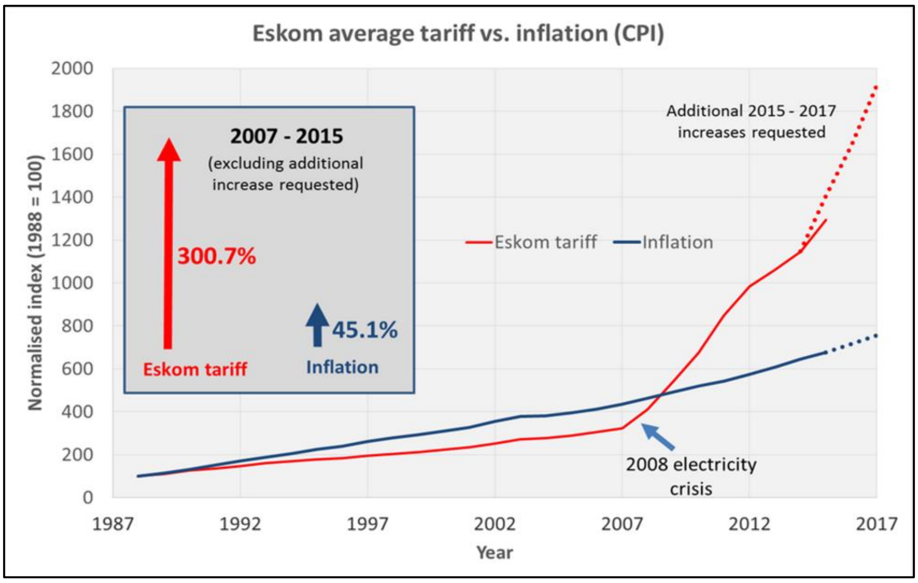

Figure 4.3 The overall average inflation increases in electricity prices between 1988 and 2015, and projected increases up to 2017 (Moolman, 2017)

The subsequent price increases forced consumers to become more energy efficient due to targeted load-shedding and the compounding effect of increasing tariffs (Castellano *et al.*, 2015). In fact, in 2014, large electricity users including mining operations were requested by ESKOM to reduce consumption in order to ensure the continued supply of electricity (Du Plessis *et al.*, 2014). Consequently, mining companies have struggled to adapt to the unplanned bottleneck and above-inflation electricity tariff increases and many operations have modified their mining methods and electricity consumption patterns (Ernst and Young Global Limited, 2014).

The current and future electricity capacity building programmes are expensive and have to factor in levelised costs, and thus cheap electricity cannot continue (Ting, 2015) and consumers should expect continued above-inflation electricity tariff increases. Additionally, high international crude oil prices have resulted in the rising cost of diesel fuel that increased at more than 15% per annum (Montmasson-Clair, 2016; Rupprecht, 2017). Figure 4.4 illustrates that the annual electricity and diesel tariff increases between 2008 and 2014 were the major components of the cost inflation affecting mining operations thus having a negative impact on the overall profitability of the mining companies in South Africa (Rupprecht, 2017; Minerals Council South Africa, 2017).

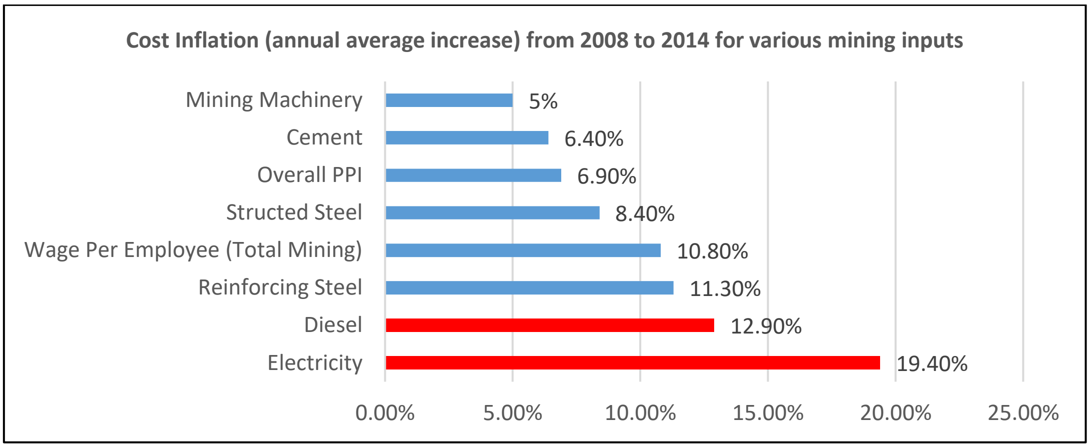

Figure 4.4 The annual average price increases between 2008 and 2014 for the major components of cost inflation affecting the mining industry in South Africa (Rupprecht, 2017)

The implementation of a carbon tax will further increase mine production costs as these will be levied over and above the yearly electricity and diesel price increases, and should thus be viewed as a major driver for energy management and reduction. It is thus of utmost importance that mining companies understand and measure the sources of their GHG emissions, which in turn will allow them to manage these emissions sources and ultimately reduce their carbon footprint (Montmasson-Clair, 2016). To achieve this, they need to better quantify their energy usage.

Figure 4.5 shows that the South African industrial sector accounted for 36% of total energy demand in 2015 and Figure 4.6 shows that the mining sector consumed 16% of the 36% (Ratshomo and Nembahe, 2018). Therefore, the mining industry consumed approximately 6% of South Africa’s total energy supply (Ratshomo and Nembahe, 2018). In its energy mix, the mining industry consumes around 15% of South Africa’s total annual electrical energy output (ESKOM Demand Side Management Department, 2010; Montmasson-Clair, 2016).

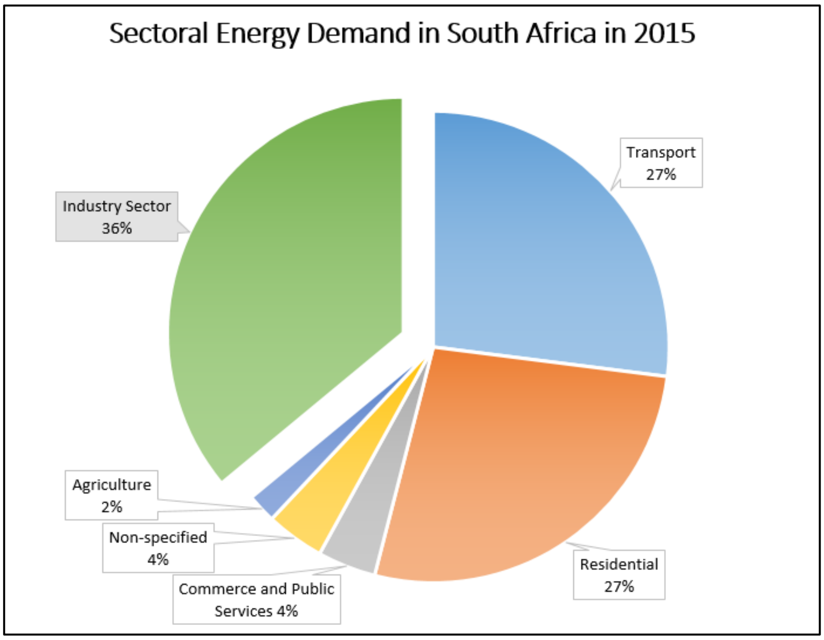

Figure 4.5 The sectoral energy demand for South Africa in 2015 (Adapted from Ratshomo and Nembahe (2018))

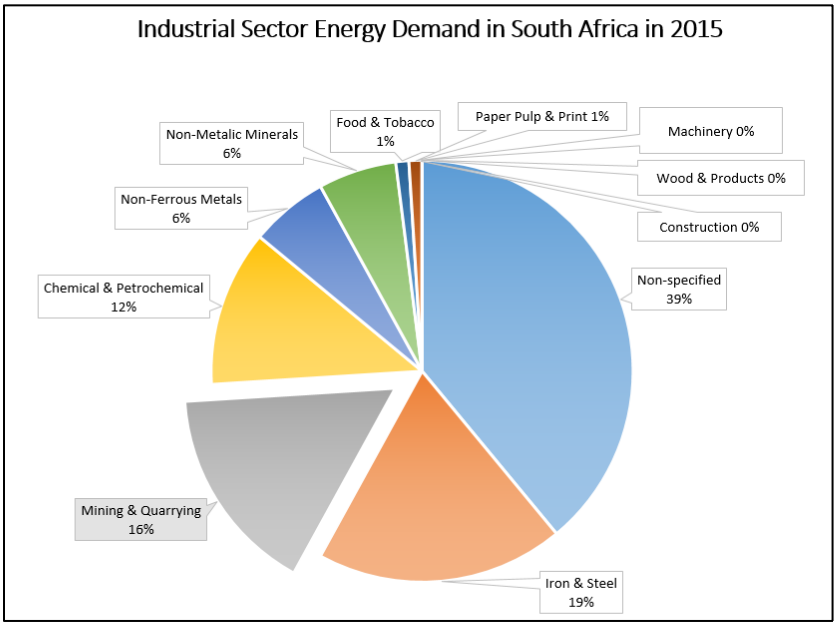

Figure 4.6 The industrial sector energy demand for South Africa in 2015 (Adapted from Ratshomo and Nembahe (2018))

Figure 4.7 shows the mining sector energy mix in 2015 and shows that a typical mining operation consumed 60% of electricity, 38% of petroleum products and

2% of coal and gas combined (Ratshomo and Nembahe, 2018). However, it should be noted that individual mine energy requirements and energy mix vary greatly depending on various factors such as commodity, type of ore being mined, the depth of mining, surface or underground mining operation and mining method employed (Ryan, 2014).

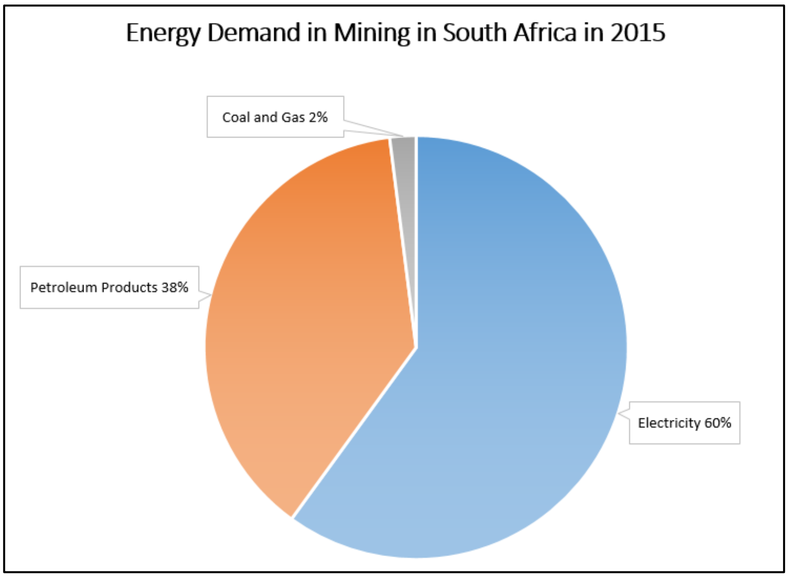

Figure 4.7 The South African mining sector energy mix in 2015 (Adapted from Ratshomo and Nembahe (2018))

4.3 Quantification of Platinum Mining Energy Consumption

Ryan (2014) found, from company sustainability reports, that the platinum industry is greatly dependent on electricity usage, with some large platinum producers using over 70% electricity in their energy mix. The platinum industry consumes approximately 33% of the mining industry's electricity output, second to gold electricity consumption of 47% (ESKOM Demand Side Management Department, 2010; Montmasson-Clair, 2016).

The process of underground mining requires copious amounts of chemical, thermal, electrical and human energy to break large volumes of rock and move the broken rocks to surface against the force of gravity. Within typical underground deep mining operations, Fraser (2017) illustrates in Figure 4.8 that energy is required for various essential mining processes such as vertical and horizontal transportation for workers and materials, ventilation, cooling and fans, compressed air, diesel to power mechanised equipment, buildings on surface, pumping and explosives to break rocks.

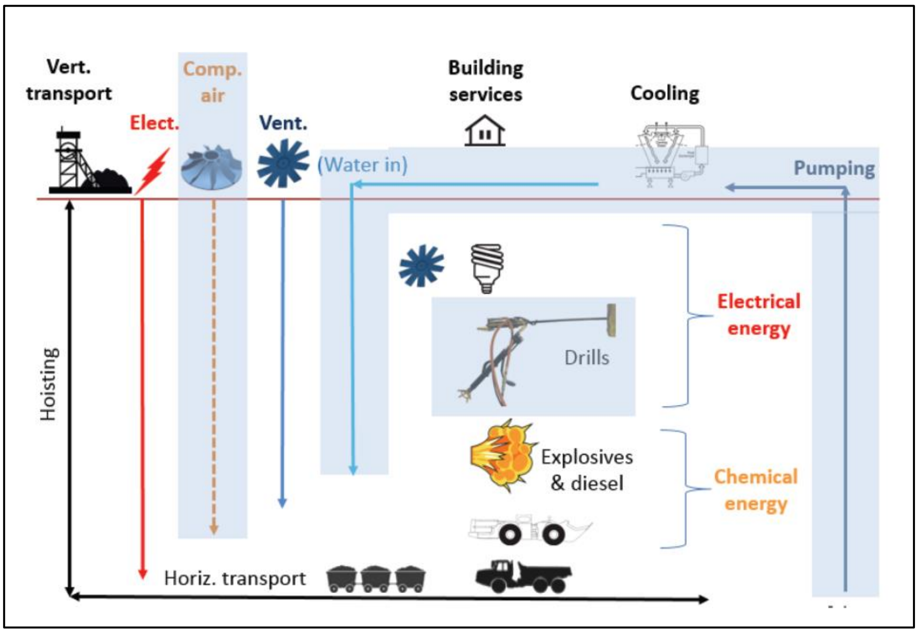

Figure 4.8 Energy utilisation in a typical deep level underground mine (Fraser, 2017)

Ventilation, refrigeration, pumping and compressed air are usually the largest electric energy consumers in conventional underground mines, especially as mining depths increase and higher virgin rock temperatures are encountered and workplaces are situated further away from the shaft (Bluhm *et al.*, 2001). The effects of greater depth on these consumers are briefly discussed below:

a) Mine ventilation, a health and safety requirement, is also achieved with powerful fans that remove noxious gases, excess moisture and dust from the underground mining cavity and provide fresh air for workers. Greater mining depths result in new cavity volumes that have to be ventilated at greater distances from the shaft. At some underground operations, ventilation fans operate 24 hours and seven days a week (ESKOM Demand Side Management Department, 2010);

b) Refrigeration and cooling systems are required to reduce temperatures in underground working areas to an acceptable legislated working temperature. Similar to ventilation, greater mining depths add more load on refrigeration requirements;

c) Pumping is essential to transport drinking and service water at often-high pressures to various underground working areas and subsequently to dewater the mine. The greater the depth and water pressure required, the more powerful and electricity hungry the pumps are; and

d) Compressed air is used as an energy source for pneumatic drilling equipment underground as well as fresh air for refuge bays. Natural wear and tear of the pipes often causes leakages resulting in compressed air wastage. In South African conventional deep underground platinum mines, compressed air contributes almost a quarter of the mines energy costs (Johnson and Fourie, 2012).

In an industry-wide study, ESKOM Demand Side Management Department (2010) quantified the energy consumption of various mining processes for a typical deep level underground mining operation to assist mines to reduce their energy consumption. ESKOM Demand Side Management Department (2010) found that processing plants used 19% of total mine energy with the most energy intensive underground activities and processes being material handling (23% energy consumption), compressed air (17% energy consumption), pumping (14% energy consumption), ventilation (7% energy consumption) and refrigeration (5% energy consumption). All the consumption categories and percentages are shown in Figure 4.9. ESKOM Demand Side Management Department (2010) found that most underground activities rely on electricity driven motors resulting in motors accounting for almost 60% of the mining industry’s electricity consumption.

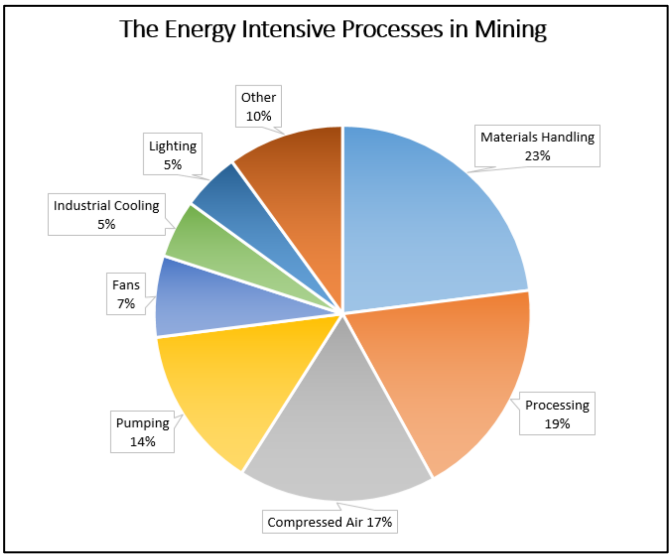

Figure 4.9 The quantification of energy consumption for various mining processes and activities (Adapted from ESKOM Demand Side Management Department (2010))

Tshisekedi (2009) did a study to benchmark the quantification and evaluation of the costs of energy consumption in the gold and platinum industries. Tshisekedi (2009) included a detailed breakdown of the consumption and cost patterns at conventional and mechanised gold and platinum mines for the period of one year at various depths and levels of mechanisation. Data was collected using a survey, discussions and interviews. Anglo American Platinum and Northam participated and provided information for six mines in total (Tshisekedi, 2009). This study showed that 133 kWh is required for a tonne of ore milled and that approximately 1.8 GJ of energy is required to produce an ounce of platinum (Tshisekedi, 2009).

Furthermore, a percentage breakdown of energy consumption of various production, support services and beneficiating activities are presented in Figure 4.10. Tshisekedi (2009) found that for the platinum mines in the study, the most energy intensive activities were processing plant (49% energy consumption), pumping (20% energy consumption), mining activities such as winding, hoisting and loading (20% energy consumption), ventilation and refridgeration (6% energy consumption) and compressed air (8% energy consumption).

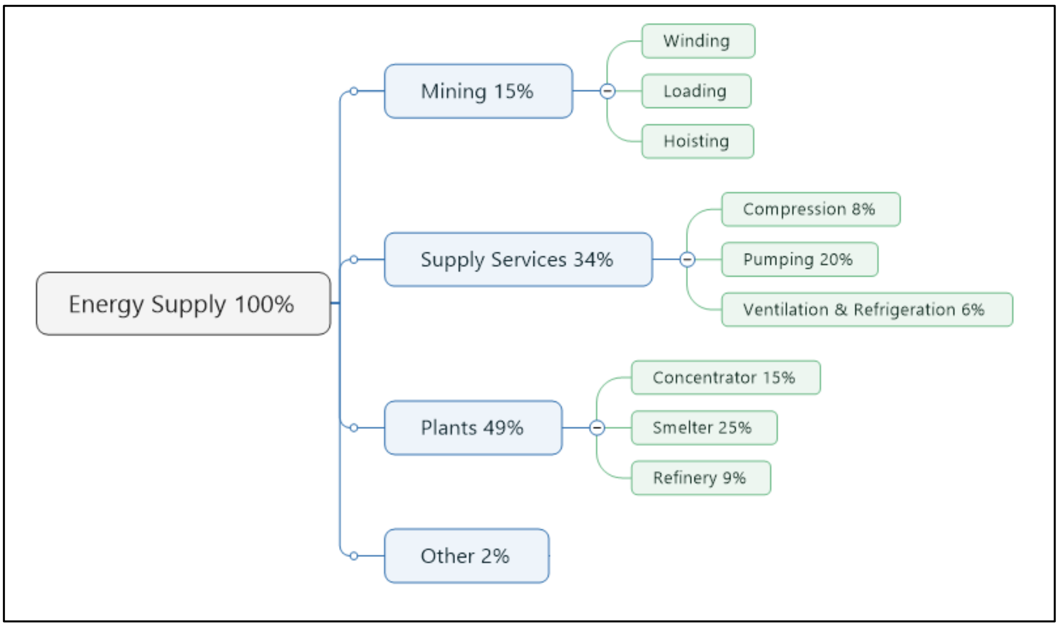

Figure 4.10 Platinum mines average energy consumption from mining to processing (Tshisekedi, 2009)

Table 4.2 shows the energy benchmarking results for platinum mines of varying degrees of mine mechanisation (Tshisekedi, 2009). Tshisekedi (2009) found that for the platinum mines in the study, the average electricity used was 80% and the average liquid fuels consumed was 20%, and that there was little variation (~5%) between electricity consumption at mines with low mechanisation and hybrid. The results obtained by Tshisekedi (2009) differ from the ESKOM Demand Side Management Department (2010) study because the ESKOM Demand Side Management Department (2010) study is industry-wide. Tshisekedi (2009) highlighted one of the mines as being an outlier because it was the deepest mine but had the lowest energy consumption as a result of the use of hydropower as a source of energy underground. Note that the above-mentioned Northam data was acquired for the Zondereinde mine. Tshisekedi (2009) cautions that results obtained are only indicative for further studies since only one-year's data was used.

Table 4.2 Average energy consumption benchmark for Platinum mines - based on degree of mechanisation

Degree of Mechanisation	Average Energy Consumption (%)	
	Electricity	Liquid Fuels
Low	77	23
Hybrid	82	18
Total Average	80	20

Source: Tshisekedi (2009)

Whilst most mines publish their overall energy usage in annual reports as part of sustainability reporting (Glaister and Mudd, 2010), not much information is publicly available about detailed energy and water consumption of individual mines. Glaister and Mudd (2010) undertook a detailed review of energy and water consumption information extracted from sustainability reporting of several platinum mines in South Africa and Zimbabwe over a varying number of years. Glaister and Mudd (2010) established that the average unit energy consumption for underground mining at platinum mines are 239 MJ/t (0.239 GJ/t) for Bafokeng- Rasimone mine, 404 MJ/t (0.404 GJ/t) for Lebowa mine, 292 MJ/t (0.292 GJ/t) for Amandelbult mine, 295 MJ/t (0.295 GJ/t) for Rustenburg mines and 324 MJ/t (0.324 GJ/t) for Union mine (shown in Table 3.3). Glaister and Mudd (2010) also found that electricity represents the dominant form of energy used in platinum mining operations (shown in Table 4.4). The variation spread was between 60% and 90% for the dominant platinum mining companies. This correlates with a study by Ratshomo and Nembahe (2018) that quantified the average electricity consumption of underground mines as 60%. This can be attributed to the nature of narrow reef underground mining largely focused on conventional mining layout and minimising dilution (Glaister and Mudd, 2010).

Table 4.3 Average energy consumption for mine and concentrator at various platinum mines in South Africa

Individual Project / Mine	Mining (MJ/t rock)	Milling (MJ/t Ore)	Energy (GJ/kg PGM)	Energy (MJ/t Ore)
Bafokeng – Rasimone	239 (2)	154 (2)	116 (7)	409 (7)
Lebowa	404 (2)	153 (2)	164 (7)	606 (7)
Mogalakwena	21 (2)	232 (2)	201 (7)	500 (7)
Amandelbult	292 (2)	148 (2)	106 (7)	465 (7)
Rustenburg	295 (2)	160 (2)	132 (7)	475 (7)
Union	324 (2)	130 (2)	190 (7)	521 (7)
Twickenham	80 (1)	-	28.5 (1)	107 (1)
Mototolo JV	-	170 (2)	74.8 (2)	196 (2)
Crocodile River	-	-	145 (1)	310 (1)

Source: Glaister and Mudd (2010) - compiled using sustainability reporting information over the number of years in brackets

Table 4.4 Average energy consumption at various platinum mining companies in South Africa

Company/Group Totals (Mine, Concentrator and Smelter)	Direct Energy	Indirect Energy (Electricity)	Energy (GJ/kg PGM)	Energy (MJ/t Ore)
Implats	37.2% (5)	62.8% (5)	254.6 (5)	962.3 (5)
Lonmin	20.1% (4)	79.1% (4)	167.6 (6)	469.3 (6)
Northam	7.9% (4)	92.1% (4)	-	-
Anglo Platinum	23.6 (4)	76.4% (4)	-	-

Source: Glaister and Mudd (2010) - compiled using sustainability reporting information over the number of years in brackets

Glaister and Mudd (2010) further found that there is a strong correlation between energy consumption and PGM production and that declining grades have a significant impact on unit energy consumption (Glaister and Mudd, 2010). Glaister and Mudd (2010) also included an open pit mine whose energy usage was substantially lower due to the nature of bulk mining techniques, however at the expense of removing large volumes of waste and a larger environmental footprint. Glaister and Mudd (2010) found that the unit energy consumption at a typical platinum mine is between 100-225 GJ/kg PGM. The results were obtained from either mine and concentrator data or mine, concentrator and smelter data. As illustrated in Figure 4.11, Glaister and Mudd (2010) found that mining activities consumed the most energy (41%) and that milling and smelting activities consumed close to 25% per activity for Anglo Platinum mines.

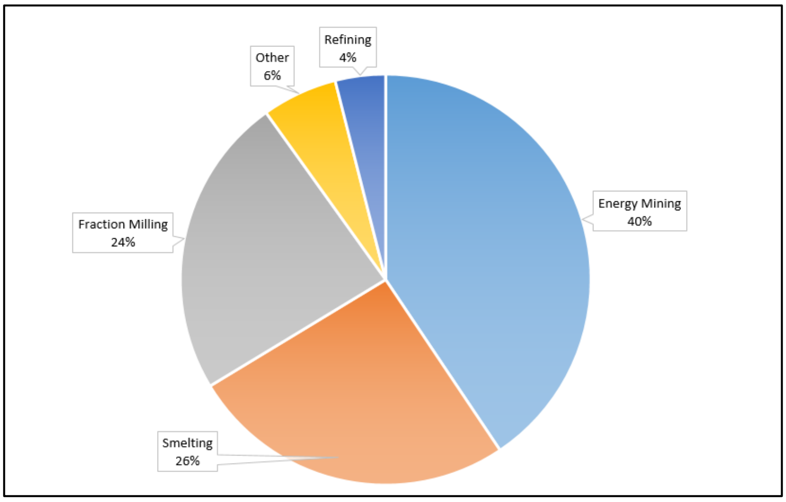

Figure 4.11 Anglo Platinum average energy consumption breakdown using data collected over 4 years (Glaister and Mudd, 2010)

Bleiwas (2011) undertook a study to quantify the energy consumption for platinum mines and found that for general platinum mining, the energy consumption for mining and processing was between 100 and 250 kWh/t ore (0.36 and 0.9 GJ/t ore). The variability in this quantification is due to the structural differences between the operations in the study (Bleiwas, 2011). The data inputs into this quantification came from mines across the Bushveld complex, different data sources including the data collected by Tshisekedi (2009), and mines with varying degrees of mechanisation, depths and mining methods (Bleiwas, 2011). Table 4.5 summarises the unit energy consumption for various platinum mines obtained from literature.

Table 4.5 Platinum mines unit energy consumption from literature

Reference	Mining company/ shaft	Mining method	Unit Energy consumption (GJ/ tonne)	Mining activities analysed
Bleiwas (2011)	General PGM	Conventional, hybrid and mechanised	0.36 to 0.90	Mining and processing
Tshisekedi (2009)	General PGM	Conventional and mechanised	0.479	Mining
Glaister and Mudd (2010)	Bafokeng	Conventional	0.239	Mining
Glaister and Mudd (2010)	Lebowa	Conventional	0.404	Mining
Glaister and Mudd (2010)	Amandelbult	Conventional	0.292	Mining
Glaister and Mudd (2010)	Rustenburg shafts	Unspecified	0.295	Mining
Glaister and Mudd (2010)	Union	Conventional	0.324	Mining

4.4 Mine Energy Efficiency Efforts

Section 3.2 highlighted the electricity crisis that South African mining companies face with respect to electricity availability, above inflation electricity cost increases and the drive towards a reduced carbon footprint. Du Plessis *et al*. (2014) states that in 2012 energy represented more than 20% of the mine's total costs. The main drivers for energy efficiency efforts are the magnitude of potential cost savings and the simplicity of application of energy saving solutions in an underground environment (Ryan, 2014). Du Plessis *et al*. (2014) states that even a minor saving in energy consumption of 1% of the total energy budget can amount to approximately US$ 80 000 saving per annum.

Many of the efficiency measures are focused low hanging fruits that make business sense and have minimum impact on production activities, such as demand side energy management and process optimisation. Du Plessis *et al.* (2014) undertook a study to investigate the energy cost efficiencies that would result from the implementation of integrated energy management and control strategies focused on offsetting the rising costs spent on ventilation, cooling and refrigeration at mines. These strategies included ventilation and cooling on-demand, which entails using the cyclical nature of conventional mining by reducing the speed of ventilation fans and the intensity of refrigeration during blasting when the working personnel are vacated from working areas (Du Plessis *et al.,* 2014). Du Plessis *et al.* (2014) found that these strategies were not only technically feasible but resulted in a large cost saving.

Additional strategies include a detailed understanding of energy usage and subsequent feasibility studies to reduce consumption, the use of alternative energy source and investment in innovative environmentally friendly solutions that use platinum in their design such as fuel cells (Ryan, 2014). Measures being implemented by mining companies to improve energy efficiencies include replacement of compressed air powered equipment such as drills with hydraulic or electrical and hydraulic powered equipment (Ryan, 2014; Fraser, 2017). The rationale behind this is to mitigate the inefficiencies presented by compressed air and the opportunities presented by more efficient energy sources such as electricity and hydropower (Ryan, 2014; Fraser, 2017). Fraser (2017) further provides a range of solutions mines may use to improve production and reduce energy consumption such as the use of jigs to improve drill accuracy resulting in a reduction of blast damage, poor face advance, dilution and wasted explosives; smart remote controlled scraper winches to ensure safety and automated cleaning of blasted areas immediately after a blast occurs; load shifting of pumps to times when electricity costs are cheaper.

Alternative energy sources and generation such as biomass, solar power plants, hydropower, natural gas-powered fuel cells and core generation through waste-heat energy recovery and biodiesel are strategies mining companies such as Anglo American Platinum and Lonmin are driving and exploring to not only reduce their carbon footprint but also to address the availability of supply and to improve the competitiveness of mining operations (Montmasson-Clair, 2016). Montmasson-Clair (2016) notes that these intervention measures are driven on a company level and are either being trialled or are at a conceptual/ feasibility study phase.

4.5 Conclusion

In South Africa, energy has played and continues to play a critical role in the country's current and future industrial and economic development. Most of the South African electricity and energy comes from coal-fired power stations, with the national power utility ESKOM dominating the electricity sector. The historically cheap availability of electricity allowed the mining industry to grow and flourish.

However, since the electricity crisis in 2008, electricity supply has become constrained and electricity prices have soared and continue to increase year on year. The mining industry has seen double-digit electricity and diesel price increases yearly and this trend is predicted to be exacerbated considering the heavy reliance on fossil fuel energy and the introduction of a carbon tax.

Energy is an important input resource for essential current platinum mining processes that are dominated by ventilation, refrigeration, pumping and compressed air. Several authors have tried to estimate energy consumption figures for platinum mining.

Efficiency improvements in energy consumption (particularly electricity consumption) by mining companies have focused on quick wins that make business sense and have a minimal impact on production. However, the projected future electricity price increases will soon outstrip these quick wins and greater interventions will be required.

5 THE SOUTH AFRICAN WATER LANDSCAPE

5.1 Introduction

South Africa is a water-scarce, semi-arid country with an average annual rainfall of about 450 mm (much lower than the world average of approximately 860 mm per year) (Department of Water Affairs, 2013) and with an evaporation potential of four times its average rainfall (De Lange, 2016). Additionally, its precipitation patterns are unevenly distributed, with only 9% of rainwater finding its way into the river systems (De Lange, 2016). Its renewable water resource in 2010 was only 1048 m^3/person/year which is also well below the global average renewable water resource of 8210 m^3/person/year (Haggard, 2015). This water scarcity is exacerbated by severe droughts, extreme weather conditions, fluctuating rainfall, limited underground aquifers, lack of investment and poor maintenance of water infrastructure, the impacts of rapid urbanisation and global climate change (Department of Water Affairs, 2013; PricewaterhouseCoopers, 2016).

South Africa is reliant on water supply from neighbouring countries. It is predicted that the future water demand will outstrip the currently available supply by 2025 (Ranchod *et al.*, 2015) and that the main threats to security of supply are deteriorating water quality and failing water infrastructure. Water quality is already fast becoming a major factor that negatively affects the usability of this scarce resource, with research indicating serious concerns about the water quality in the country's rivers and dams (PricewaterhouseCoopers, 2016). Additionally, 15% to 35% of the total service water goes unaccounted for in South Africa, which implies that the improved accounting of the water systems is essential to ensure appropriate allocation of this resource and informed decision-making (De Lange, 2016). The above-mentioned challenges, coupled with an increased demand on already constrained water resources, intensify the need to prioritise water allocation by geography, sector and quantity (Department of Water Affairs, 2013), forcing the South African government to make difficult choices and compromises between the needs of agriculture, industry, rapidly expanding urban centres and citizens.

Prior to 1994, the legal framework tied the ownership of natural resources, including water, to ownership of the land. After the first democratically held elections in 1994, the framework of the ownership of natural resources changed and became collective property of all citizens, placing the natural resources under custodianship of the South African government (Adler *et al.*, 2007). Furthermore, the South African constitution entrenched water as a basic human right, thus placing a legal responsibility on the government to provide equal access to sufficient water supply to all its citizens (Adler *et al.*, 2007). However, prevailing evidence suggests that large quantities of water are being wasted, degraded, polluted, misallocated and insufficiently funded by the government, despite mature water management and supply infrastructure (De Lange, 2016).

5.2 Water and Mining in South Africa

Mining and water resources are intrinsically interlinked because mining activities are not only dependent on the accessibility and the availability of water resources, but also have an impact on the surface and ground water systems (Mudd, 2008). Historically, the South African mining industry had access to cheap and readily available water, which was regulated differently for mining than for other industries in order to enable the mining industry to grow and flourish (Adler *et al.*, 2007). However, after nearly a century of mining, the negative and unintended consequences of poor water use and treatment policies associated with mining have resulted in modified natural water tables, acid mine drainage and degraded water quality (Adler *et al.*, 2007).

When compared against other industries, even though mining uses relatively small quantities of water, it is associated with substantial water quality risks, such as uncontrolled discharges, alterations to natural flow pathways, collapses and/or leakages of slimes dams (Northey *et al.*, 2016). The above-mentioned risks are dependent on factors such as the mineralogy and geochemistry of the ore body, mining method, mine discharge management, unlined mine waste storage and ore processing methods (Northey *et al.*, 2016). The primary sources of water pollution/contamination may vary from being saline, heavy metal, or acid drainage, but the impacts of contamination could be long lasting (Northey *et al.*, 2016).

Acid mine drainage represents one of the major challenges in the South African post-mining landscape, representing one of the biggest threats to contamination of the available water resources (Ranchod *et al.*, 2015; De Lange, 2016). A major source of this pollution originates from abandoned and non-rehabilitated mines, where dewatering no longer takes place and underground water interacts with the exposed sulphide minerals from the ore, explosives and chemicals previously used and/or cyanide from backfill operations and becomes highly acidic (Department of Water Affairs and Forestry, 2008; Ranchod *et al.*, 2015). This acidic water gradually rises to the surface and contaminates the near surface acquirers as well as springs and river systems (Department of Water Affairs and Forestry, 2008; Ranchod *et al.*, 2015).

Even when rehabilitation of mines takes place, the post-mining hydrological profile of the mine site can be negatively affected compared to the pre-mining state (Northey *et al.*, 2016), especially if excessive withdrawal from the local aquifers had taken place (Haggard *et al.*, 2015). These may lead to changes in the local river flow regimes, lowering of the local aquifer water levels as well alteration of the groundwater flow patterns (Haggard *et al.*, 2015).

The aforementioned negative externalities associated with mining and water resources have resulted in stricter legislation governing water rights and mining with emphasis on the environmental impacts of mining in particular water management (Mudd, 2008). Going forward, the mining industry needs to be aware that its social licence to operate with the neighbouring communities and mining companies' reputations are strongly linked to the way it uses and manages available scarce water resources (Adler *et al.*, 2007). Failure to address water management issues will potentially result in competition for the resource and possible mining community conflicts, especially since many mines are surrounded by communities that are struggling to attain access to water.

5.3 Quantification of Platinum Mining Water Consumption

In South Africa, water consumption consists of agriculture, industry (including mining and power generation) as well as domestic and urban users (Ranchod *et al.*, 2015). Mining is one of the six major water-use sectors in South Africa (Department of Water Affairs, 2013). Figure 5.1 shows that the mining industry consumed approximately 5% of the total water in South Africa in 2010 (Statistics South Africa, 2012; Haggard *et al.*, 2015). In 2010, the 5% was equivalent to 236 million m^3 of water (Statistics South Africa, 2012; Haggard *et al.*, 2015). However, accurately calculating mine water usage is complicated since mining consumes grey water (re-used water that is used in mining processes), blue water (water from the ground and surface that is used for mining processes) and green water (rainwater that is used for mining processes) (Haggard, 2015).

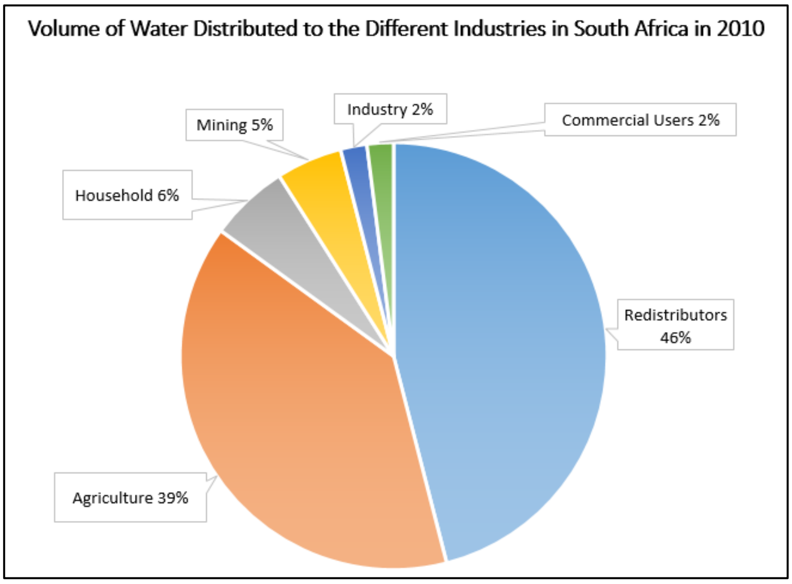

Figure 5.1 Distribution of water volume to the different sectors in South Africa in 2010. Source information from Statistics South Africa (2012)

Within a typical underground mining environment, water is used for a variety of activities such as, but not limited to, dust suppression, the operation of mining equipment, cooling, sanitation, drinking, cleaning and sweeping and backfill (Peake *et al.*, 2002; Department of Water Affairs and Forestry, 2008). The water demand in the underground working environment is dependent on the equipment used, mining method, control systems as well as cycle times employed (Peake *et al.*, 2002). Due to the high geothermal gradient of platinum rocks and as mines get deeper, some mining operations attempt to cool the working areas by cooling water on the surface in refrigeration plants and then transporting it underground in the form of ice or chilled water. Additionally, workers often use potable water to cool themselves down since the heat has a negative impact on productivity (Stephenson, 1983; Peake *et al.*, 2002). Because water can be found everywhere in the underground working environment, water wastage in stopes is common (Peake *et al.*, 2002).

Another important aspect of water usage in underground mining operations is the direct relationship between the quantity of water used and production levels, which implies that mines with high tonnage outputs use more water. It is also important to note that water requirements tend to change during the mine life cycle and are impacted by the alteration of host terrain, modification of water reservoirs, increases in production, extreme weather events and change in the metallurgical properties of the ore body resulting in change in processing requirements (Northey *et al.*, 2016).

There are various sources of water that are used and that occur in the underground working environments. Examples are potable water (that is purchased from the municipality or produced on site), raw water (from rivers, dams or boreholes), processed water (from effluent treatment plants or mining activities), and harvested water (from rain and storm water runoff) (The Stakeholder Accord on Water Conservation, 2009). Another source of underground raw water is fissure water. Fissure water is water ingress into the working areas from in-lying and/or over-lying aquifers located in the immediate vicinity of the mining operation (Department of Water Affairs and Forestry, 2008). The aquifers may be punctured by geological structures, exploration, cover or support drillholes and mine shafts

(Department of Water Affairs and Forestry, 2008). Adjacent mining operations, which are linked through underground developments, could also be at risk of inter-mine flows (Department of Water Affairs and Forestry, 2008). Any water ingress poses a safety risk to a mining operation and not only results in additional costs associated with dewatering (Department of Water Affairs and Forestry, 2008), but poses complications when trying to accurately account for raw water use. Dewatering of excess water underground would result in increased electricity costs because larger pumps with greater capacity are required to maintain a safe working environment (Bergkvist, 2012).

A typical underground mine service water circuit is shown in Figure 5.2 (Department of Water Affairs and Forestry, 2008). It includes mine service water reticulation systems to deliver service water to working areas, drains and/or sumps to collect used water from underground working areas to underground water treatment facilities, clean water and mud underground storage facilities and dewatering facilities and pumps to transport clean settled water and mud to the surface (Department of Water Affairs and Forestry, 2008).

A major flaw in the underground water management system is the lack of flow meters installed throughout the service water circuit (Department of Water Affairs and Forestry, 2008). In most cases, the amount of water is measured as it enters the underground workings and when it is pumped back to the surface, with water demand/balance calculated by subtracting one from the other (Peake *et al.*, 2002). It is thus difficult to identify working areas that consume excessive volumes of water, complicating water management and improvement efforts (Department of Water Affairs and Forestry, 2008). Metering systems measure the volumes of effluent, potable water, harvested rainwater and raw water. Where water cannot be metered, such as ground water ingress, the water balance provides a good estimation of the excess water (The Stakeholder Accord on Water Conservation, 2009).

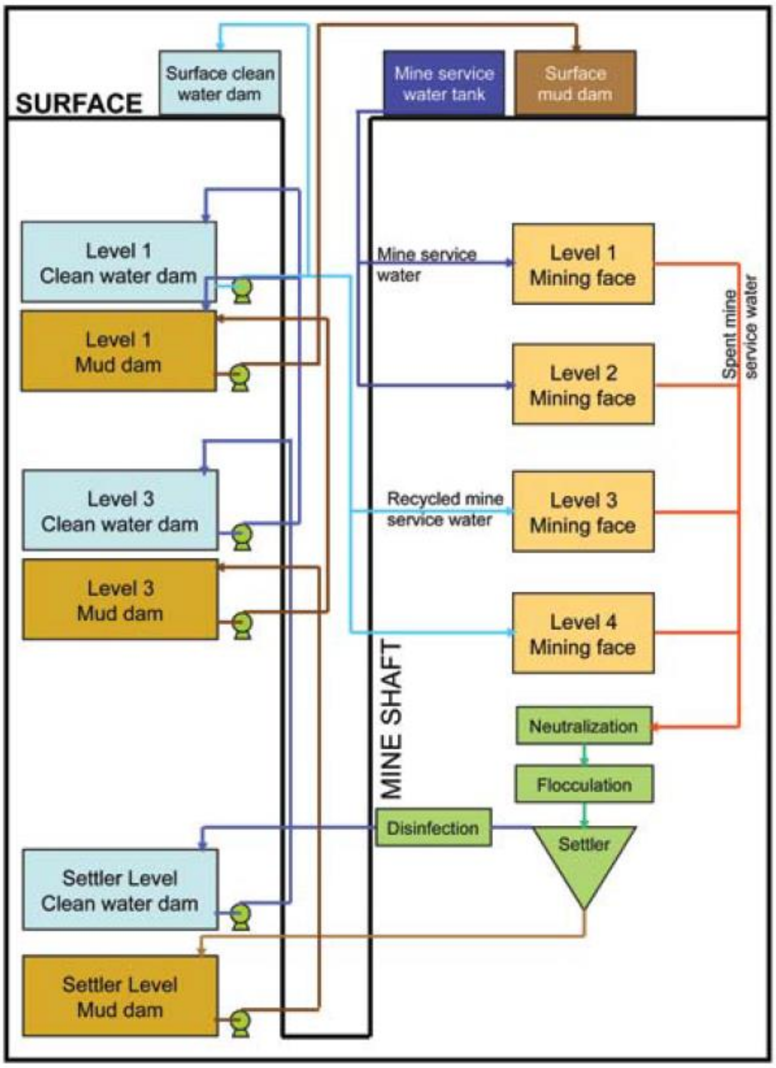

Figure 5.2 A typical underground mine service water circuit (Department of Water Affairs and Forestry, 2008)

A typical underground water balance should consider all types of the above-mentioned water use and flows. Figure 4.3 is an example of a water balance developed in 1990 for the gold mining sector and shows the general water use patterns (Department of Water Affairs and Forestry, 2008). There are no publicly available water balances for the platinum mining industry, hence this water balance serves as a reasonable starting point for a typical platinum mine that has major cooling requirements (Department of Water Affairs and Forestry, 2008). The overall water balance (positive or negative) could assist in assessing water risks at mining operations (Northey *et al.*, 2016). Water-positive operations could be characterised by excessive accumulation of water in dams, ponds and mine voids, due to high precipitation, requiring discharges when storage capacity is reached (Northey *et al.*, 2016). Water-negative operations may be characterised by high evaporation and frequent draws of potable water from municipalities or water reservoirs (Northey *et al.*, 2016).

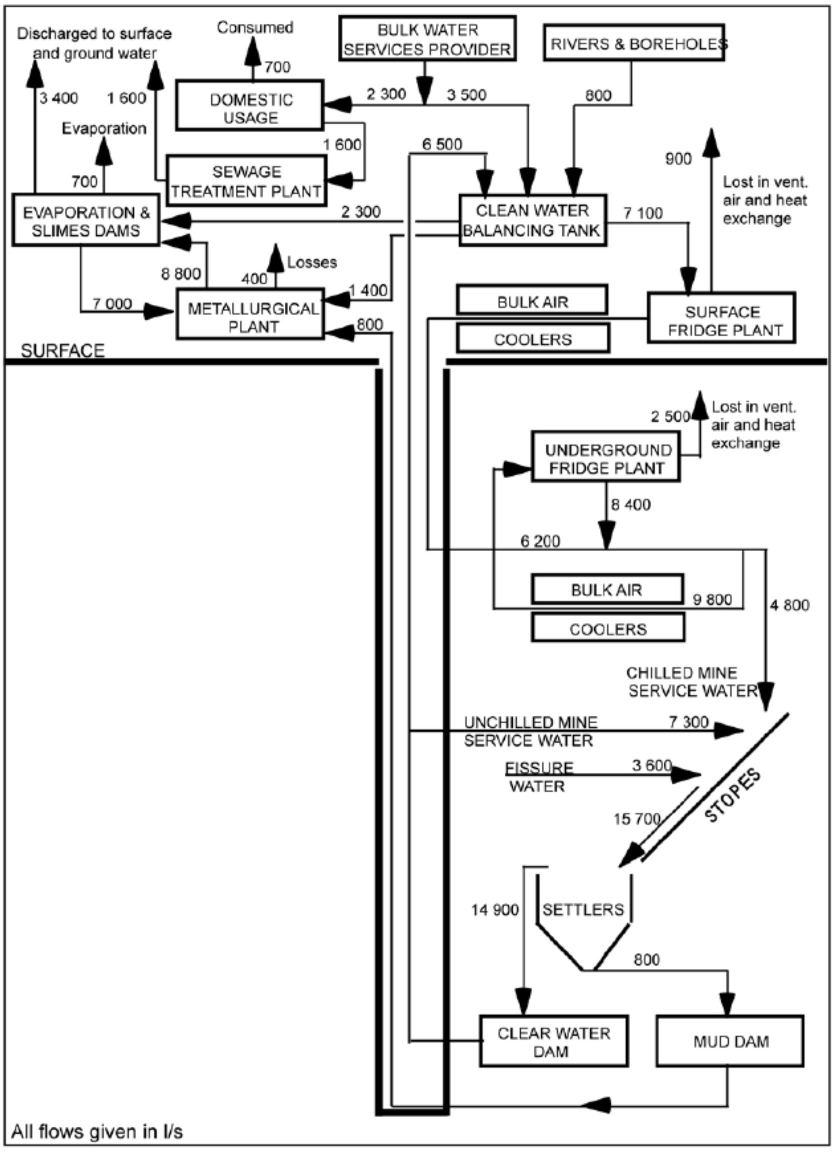

Figure 5.3 The water balance for the gold mining industry in 1990 (Department of Water Affairs and Forestry, 2008)

In order to account for water consumption, many platinum mining companies are now reporting their water data for individual mines or the entire company through sustainability reporting tools such as Global Reporting Initiative (GRI) and CDP Water (Northey *et al.*, 2016). Glaister and Mudd (2010) found that although there has been an increase in water consumption reporting in sustainability reports by platinum companies, the reporting mainly covers total water consumption and water discharges. Adding information regarding recycled water and water resources used is voluntary and hence under-reported (Glaister and Mudd, 2010). Additionally, water quality is only reported when there are discharges into the environment; however very limited information is provided (Glaister and Mudd, 2010). From information available in sustainability reports, the authors undertook a detailed review of water consumption extracted from sustainability reporting of several platinum mines in South Africa and Zimbabwe over a varying number of years.

The average water consumption at various platinum mines in South Africa in the review is shown in Table 5.1 (Glaister and Mudd, 2010). Glaister and Mudd (2010) found that estimated historical water consumption for mining, concentrating and smelting from 1955 only marginally increased from 182 m^3/kg PGM and 1.35 m^3/t ore in 1955 to 192 to 1612 m^3/kg PGM and 0.509 to 12.6 m^3/t ore in 2010. From the data in Table 5.1, platinum production (mining, concentrating and smelting) requires an average unit consumption of water of 356.45 m^3/kg PGM and 1.487 m^3/t ore. It should be noted that even though the water consumption data comprised of either mine and concentrator or mine, concentrator and smelter data, production data for smelting and refining was not reported by the companies in the sustainability reports and the author was not able to split the unit water consumption across these various stages (Glaister and Mudd, 2010). Glaister and Mudd (2010) found little evidence that project scales or ore grade have an impact on unit water efficiencies.

Mudd (2008) undertook a study to establish the total water required to produce a kg of platinum or to mine a tonne of platinum ore (total consumption including recycled and reused water), which is called embodied water. For platinum the study found that the average embodied water is 0.94 kl/t ore and 260 kl/kg PGM.

It is important to note that reported water data was not standardised across different platinum mines and companies and clarity of the data reported was an issue (Mudd, 2008). Precious metals had the highest embodied water per tonne largely due to low grades (parts per million) and the dilution associated with narrow tabular gold and platinum ore bodies. For precious metals and particularly PGMs, the study found that increased production does lead to improvement in water efficiencies (Mudd, 2008).

Table 5.1 Average water consumption at various platinum mines in South Africa

Individual Project / Mine	Average production (Mt ore/year)	Average production (t PGM)	Water consumption (m^3/kg PGM)	Water consumption (m^3/t ore)
Mine and Concentrator				
Bafokeng – Rasimone	2.518	9.359	235 (7)	0.828 (7)
Lebowa	1.509	6.158	385 (7)	1.397 (7)
Potgietersrust	4.830	12.416	277 (7)	0.695 (7)
Amandelbult	6.602	32.974	209 (7)	0.928 (7)
Rustenburg	11.457	44.971	229 (7)	0.828 (7)
Union	5.717	18.020	237 (7)	0.660 (7)
Twickenham	0.142	0.618	409 (1)	1.626 (1)
Mototolo JV	1.314	3.850	192 (2)	0.509 (2)
Crocodile River	0.844	2.021	1086 (1)	2.328 (1)
Mine, Concentrator and Smelter				
Northam	1.993	11.007	1612 (4)	12.600 (4)
Production weighted average			**356.45**	**1.487**

Source: Glaister and Mudd (2010) - compiled using sustainability reporting information over the number of years in brackets

Another way to define water consumption volumes is through the Water Footprint

Network (WFN) method (Haggard, 2015). A metal's water footprint is defined as the volume of fresh water used and contaminated in order to produce the metal, with blue water defined as the potable and ground water consumed, green water defined as rainwater consumed and grey water defined as contaminated water from production (Haggard, 2015). This method can be used to assess the impacts of water level changes in the area affected by a mining operation, which can inform discussions about water allocation and social licence to operate (Northey *et al.*, 2016). Ranchod *et al.* (2015) quantified the blue water footprint, including direct and indirect water consumption, of an open cast platinum mine in South Africa to be 2229 m^3/kg refined PGM. This study included mining, concentration, smelting, magnetic separation, base metal removal, and refining stages (Ranchod *et al.*, 2015). Haggard (2015) quantified the total water footprint of a platinum mine in South Africa to 806 m^3/kg PGM, of which 228 m^3/kg PGM or 1.4 m^3/t ore was attributed to blue water footprint and 578 m^3/kg PGM was the grey water footprint. The study included two concentrator plants and a smelter plant.

Another method used for quantifying water consumption is the Water Accounting Framework (WAF), which was developed within the Australian mining industry and allows consistent and comparable water consumption data publication (Haggard, 2015). The advantage of this method lies in the fact that all water inputs (for example, surface water, ground water and rain), outputs (for example, discharge, evaporation, seepage and entrainment) and diversions (for example, constructed river or rainfall and runoff supplied to nearby communities) are methodically recorded and reconciled. Additionally, the report includes a contextual statement to provide the necessary background information regarding conditions that might impact water management and an operational efficiencies statement noting re-use and recycle efficiencies at the operation (Haggard, 2015). This approach to reporting enables a mining operation to benchmark its water consumption performance against other similar operations without ambiguities as well as providing stakeholders with a comprehensive report of the mine's interaction with water (Danoucara *et al.*, 2014).

Peake *et al.* (2002) found that in-stope service water consumption for a typical drill and blast underground mine is 2.4 m^3/t rock mined (with actual service water consumption ranging between 1.5 m^3/t and 5.5 m^3/t rock mined), irrespective of the mining layout. This consumption is greater than historic approximation of water consumption in a panel of 1m^3/t rock mined and Peake *et al.* (2002) attribute this difference to poor in-stope water management such as underground water leakage and poor discipline leading to taps being left open. Poor in-stope water management may result in excess water and can have a negative impact on the productivity and costs (Peake *et al.*, 2002). This also poses a safety risk in the form of mud rushes and blocked drains and/or heat build-up from increased condensation (Peake *et al.*, 2002). Table 5.2 summarises the unit energy consumptions for various platinum mines obtained from literature.

Table 5.2 Platinum mines unit water consumption from literature

Reference	Mining company/ shaft and mining method (if known)	Unit Water consumption (kl/ tonne)
Glaister and Mudd (2010)	General PGM	0.509 to 12.6
Glaister and Mudd (2010)	Bafokeng (Conventional)	0.828
Glaister and Mudd (2010)	Lebowa (Conventional)	1.397
Glaister and Mudd (2010)	Amandelbult (Conventional)	0.928
Glaister and Mudd (2010)	Rustenburg shafts	0.828
Glaister and Mudd (2010)	Union (Conventional)	0.66

5.4 Mine Water Conservation Efforts

In order to constrain increasing levels of water usage in South Africa during the drought, restrictions were implemented in urban and industrial areas. To optimise and conserve the use of this scarce resource, South African mines have started implementing various water recycling, re-use and filtration strategies (PricewaterhouseCoopers, 2016). An important consideration for mine-specific water conservation opportunities is the local site condition, which includes mining method, geology and ore body mineralogy, as these have an impact on water use patterns (The Stakeholder Accord on Water Conservation, 2009).

To minimise water consumption, mines may focus their water conservation efforts on reducing the amount of water leaving the mine through evaporation, evapotranspiration, water in rock mined and returns to the surface water source. Practical examples of these efforts include harvesting of rainwater, re-use of the process water, and the use of effluent water from onsite processes in an unaltered or treated form as well as a reduction in consumption by the water-intensive processes (The Stakeholder Accord on Water Conservation, 2009).

Demand-side water management options frequently used by water boards are user education, efficient metering, use of water efficient fittings, pressure regulation, improved maintenance of infrastructure, and incentivising behavioural change (De Lange, 2016). These may also be employed by mining operations to reduce their water consumption. Additionally, water can be recycled and treated closer to the working areas as opposed to pumping it to the surface for recycling, potentially reducing both the water and energy consumption (Bergkvist, 2012). A reduction in water consumption in the mining process would result in an operation that is resilient to water shortages and especially during periods of drought (Haggard *et al.*, 2015).

5.5 Conclusion

Water plays a fundamental role in the society and environment and is intrinsically different from electricity in that it is possible to survive without electricity but not without water. South Africa is a water-scarce semi-arid country with 98% of available water resources already allocated. This water scarcity is further exacerbated by the impact of global climate change on water resources through frequent droughts. As the South African economy continues to expand, the water demand is predicted to outstrip the water supply, leading to unavoidable competition for available resources between different sectors and users, thus forcing the government to prioritise water allocation. In South Africa access to water is a basic human right, which will influence how government prioritises water allocation.

Although mining consumes only 3% of water withdrawn, the dialogue about mine water use and management is often viewed through the lens of the mining industry's historically troubled legacy of environmental incidents, poor water management and pollution. Within the underground mining environment, water is used for integral activities, the largest water users being cooling, drinking water, dust suppression and the operation of mining equipment. It is important, however, to note that underground water consumption is impacted by various factors such as mining method, ore body geometry and mineralogy, mining depth and mining life cycle.

There are various sources and types of water used underground with potable water being the easiest to measure. Other sources of water can be accounted for through a site water balance. A shortcoming of water consumption quantification underground is that although water is metered as it enters or exits the underground site, it is not metered within the different working areas, and hence identifying high water intensity areas is problematic. Furthermore, there is a lack of information on the water consumption for the different mining activities. As a result, it is difficult to analyse in detail, the impact of different mining methods on water consumption and in-stope water consumption is often estimated. Additionally, water is re-used, recycled and re-circulated underground, further complicating accurate water consumption accounting.

There are, however, several water reporting frameworks, such as GRI, CDP Water, WAF and WFN that researchers use to define water use intensity and consumption by mining companies and sectors. Generally, water consumption is non-standardised and there is a lack of detail to enable a good analysis of excessive consumption and/ or water-intensive areas.

In light of the historic legacy of mining and water resources and current water challenges, the mining industry understands that its social licence to operate is intrinsically linked to the way it uses and manages available resources. Current mine water conservation efforts have thus focused on reducing the use of potable water, re-using processed water and recycling underground water. Improvement in the metering and water accounting will allow the mines to identify quick wins and further enhance their water conservation efforts.

6 MODERN MINING METHODS

6.1 Introduction

Factors such as orebody geometry (depth, dip, width), rock strength, existing mining infrastructure, mineralogy and virgin rock temperature all dictate the mining method that can be implemented and the degree of modernisation that is possible (Fraser, 2017). Keeping this in mind modernisation is understood to describe:

d) The modernisation of current conventional mining operations by improving extraction efficiencies, health and safety as well as reducing operating costs through the implementation of new or improved technologies and improved operational practices without altering the conventional mining method (Minerals Council South Africa, 2017; Fourie *et al.*, 2017a; Singh, 2017; Fraser, 2017). In most cases, the mature mining infrastructure and labour complement will not be suited for mechanisation (Harrison, 2008). Figure 6.1 illustrates that this is possible for existing conventional mines characterised by reef dips between 12° and 34° and reef thickness of 1 m to 3 m (Fraser, 2017);

e) Implementation of mechanised drill and blast mining methods (for example, traditional bord and pillar, low profile (LP), extra-low profile (XLP) and ultra-low profile (ULP) bord and pillar mining methods) and machinery (for example, operator driven, remote controlled or autonomous) in narrow reef stopes (van den Berg, 2014; Fourie *et al.*, 2017a; Minerals Council South Africa, 2017; Singh, 2017; Fraser, 2017). Figure 6.1 illustrate that this is possible for reef dips between 0° and 11° and reef thickness of 1 m to 3 m (Fraser, 2017); and

f) Continuous autonomous mechanised mining by rock cutting or non-explosive rock breaking (Minerals Council South Africa, 2017; Fourie *et al.*, 2017a; Singh, 2017). Additionally, new chemical or organic methods may be employed for in-situ leaching of only the ore (Fraser, 2017). Figure 6.1 illustrates that this is possible for any reef dips and widths (Fraser, 2017).

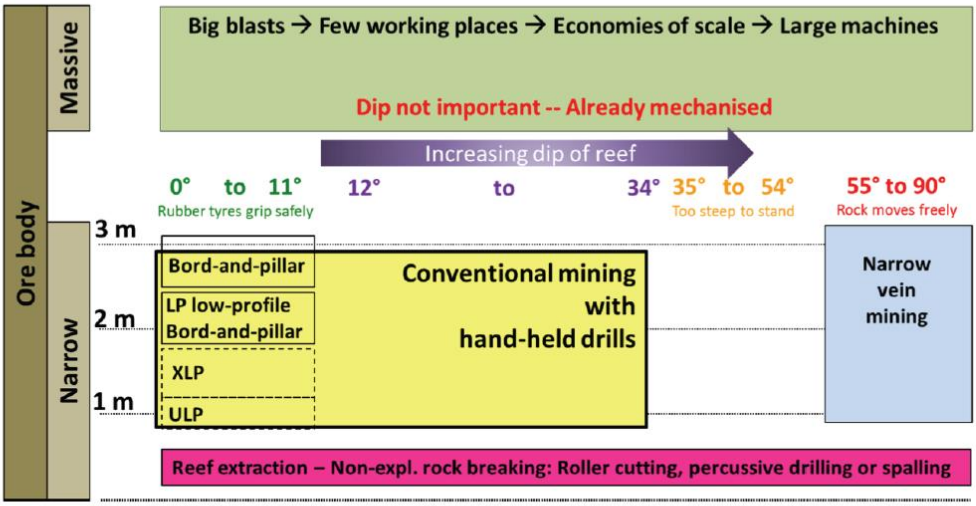

Figure 4. Hard-rock underground mining methods graphic map.

Figure 6.1 Suitability of hard rock narrow reef mining methods based on dip and reef width (Fraser, 2017)

Integral to the above-mentioned modernisation drives is the digitalisation of mining to enable faster, more efficient and cost-effective decision making based on a comprehensive understanding of the entire underground mining operation, for example, the implementation of real time information and data management and monitoring systems (Cornish and Kotze, 2015; Fraser, 2017; Minerals Council South Africa, 2017). Implementation of a fully integrated real time information and data management and monitoring system will allow for the optimisation of individual mining activities in real time as well as allow for advanced scheduling and planning of future activities (Bergkvist, 2012; Strydom *et al.*, 2017). The Minerals Council of South Africa (2017) emphasises that beyond the technical aspects of modernisation of the mining industry, the modernisation drive focuses on the responsible and sustainable use of South Africa’s valuable natural resources and the importance of people within the mining industry. Up-skilling and improving the quality of life of both employees and communities surrounding the mines are thus integral for modernising the mining industry (Minerals Council South Africa, 2017).

6.1.1 Modernised conventional mining

Modernised conventional mining methods would involve cost-effective, in many cases incremental improvements to existing processes through implementation of modern technologies, practices, methodologies and equipment, which would allow for gains in productivity (Fourie *et al.*, 2017b). This would involve introduction of more efficient drills, improvements in explosive technology, multiskilling the mining crews and increasing the panel allocation, improving transportation of labour to allow for longer time spent at the face and optimising asset utilisation, shift cycles and mine designs (Fourie *et al.*, 2017a; Rupprecht, 2017).

An example of conventional mining modernisation is Anglo American Platinum's modernised mining stope test site, which was established at one of its conventional mines to test various modern drilling and blasting technologies, as well as alternative cleaning technologies (Fourie *et al.*, 2017b). Some of the technologies that were trialled at this site are shown in Figure 6.2. For drilling Anglo American Platinum tested an electro-hydraulic drill that is lighter, produces 15% less noise and is more energy efficient than conventional drilling equipment (Fourie *et al.*, 2017b). For cleaning, Anglo American Platinum explored the use of water jet cleaning which had the potential to improve cleaning efficiencies compared to conventional face scraper cleaning (Fourie *et al.*, 2017b). For blasting, Anglo American Platinum investigated the use of throw blasting and the use of emulsion explosives, which have shown improved fragmentation and face advance (Fourie *et al.*, 2017b). Throw blasting can potentially throw at least 50% of the blasted material into the gulley and this can significantly reduce the cleaning cycle times. It is important to note that limitations imposed by the mining method, ore body, life of mine, existing mine infrastructure, economic viability and scale of the operation constrain the extent to which modernisation is possible (Fourie *et al.*, 2017a).

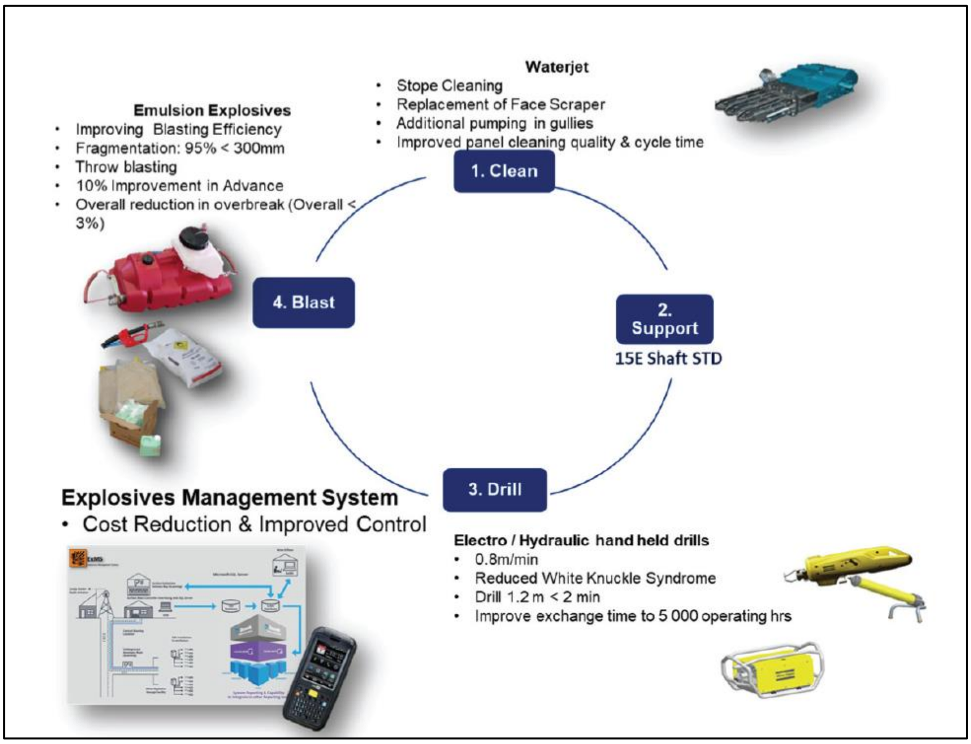

Figure 6.2 Anglo American Platinum's envisaged modernised conventional stope technology (Fourie *et al.*, 2017b)

6.1.2 Mechanised mining

Mechanisation research, development and trials have been undertaken by the South African platinum industry for the last 18 years, with good progress achieved, but much work is required to overcome the complexities of the use of this method in the South African platinum mining industry (Rupprecht, 2017). Mechanisation attempts and trials in the platinum sector in South Africa have yielded mixed results (successes and failures). The main reasons for the failures were narrow orebodies, which resulted in narrow mining width, rolling reefs, geological features such as potholes, dykes and sills, as well as lack of a proper technological implementation strategy, hence lack of buy-in by the stakeholders (Fraser, 2017; Rupprecht, 2017). Mining houses continue to invest in mechanisation for the future. For example, Anglo American Platinum aims to mechanise 80% of its mining operations by 2023 and, at the time of writing, already had several project sites testing various mechanisation equipment suites (Strydom *et al.*, 2017).

In most mechanised mining methods, development is on reef. In the optimal case, all mining cycle activities are performed by trackless machines such as electro-hydraulic drill rigs and roof-bolters for drilling and support, charging up vehicles and emulsion explosives for blasting, Load-Haul-Dump (LHD) machines for cleaning, personnel vehicles, trucks to transport ore to the surface, and mechanised rock breakers to fragment large rocks (Egerton, 2004). This implies a smaller labour complement that is more highly skilled and is required to operate machinery and equipment in much safer working conditions (Egerton, 2004). Logistics, access to ore reserves and material handling are improved. However, the shaft head grade is reduced due to the additional waste mined to create the large stopes and development required for the equipment to move around (Egerton, 2004). Increased dilution results in increased material handling cost (ore transportation) and high-energy usage in the plant for mineral processing.

The bord and pillar mechanised mining method is popular in South African underground platinum mines but is restricted by depth (Fourie *et al.*, 2017a). Bord and pillar mining methods are suitable for flat dipping (0° to 11°) wide (2 m to 3 m) reef packages and use the standard suite of mechanised equipment (Egerton, 2004). LP bord and pillar uses trackless mining equipment that has been scaled down and can exploit mining widths of 1.8 m to 2 m, such as low-profile LHDs and low-profile electro-hydraulic single boom drills (Egerton, 2004; van den Berg, 2014).

Since 2003, Anglo American Platinum has been working with various equipment manufacturers to develop XLP suites of equipment to suit the South African narrow reef mining environment (Fourie *et al.*, 2017a). XLP mechanised equipment can exploit reef widths of 1.2 to 1.7 m, and trials at various test sites resulted in limited success and the development of ULP fleet of equipment (Fourie *et al.*, 2017a). ULP mechanised mining equipment is designed to exploit reef widths of 0.9 to 1.2m, respectively (van den Berg, 2014), and was trialled by Anglo American Platinum (Fourie *et al.*, 2017a). XLP and ULP mechanised mining methods use low-profile equipment for development such as raises and drives, uses XLP and ULP equipment suites for ledging and mechanised breast mining stoping operations (van den Berg, 2014). XLP and ULP can be implemented for dips of up to 22 degrees and can operate at depth 350 to 1800 m (Fourie *et al.*, 2014), with both methods have been shown to produce high shaft head grade with minimal dilution (Fourie *et al.*, 2014). Table 6.1 provides a comparative summary of LP, XLP and ULP stoping methods and equipment (Fourie *et al.*, 2014).

Table 6.1 Summary of LP, XLP and ULP stoping methods

	LP stoping methods	**XLP stoping methods**	**ULP stoping methods**
Depth	0 – 400 m	350 – 1800 m	350 – 1800 m
Stoping width	1.8 – 2 m	1.3 – 1.7 m	0.9 – 1.2 m
Mining method	Bord and pillar	Breast mining	Breast mining
Dip	$\pm 10^0$	0^0 - 22^0	0^0 - 22^0
Production	2 100 – 3 000 m^2	2 100 – 3 000 m^2	2 000 – 3 000 m^2
Orebody	Consistent ore deposits without major faults	Consistent orebody, high extraction ratio	Fairly consistent orebody, high extraction ratio
Advantages	Low level operating complexity	Less dilution when compared to LP Low wastage introduced into plant	High-grade ore Able to deal with orebody complexities
Disadvantages	High volume tonnages Low grade High operating cost Complex infrastructure	Robust equipment Labour-intensive Highly skilled workforce Complex infrastructure	Advanced technology Highly skilled workforce Technology in proof-of-concept phase

Source: Fourie *et al.* (2014)

Figure 6.3 shows an example of a ULP fleet of equipment (similar suites available for XLP) and includes a drill rig, a roof bolter for installing support, a dozer for cleaning operations, and a sweeper for cleaning the areas where dozer cannot reach (Fourie *et al.*, 2014). Figure 6.4 (a, b and c) shows an XLP dozer, drill rig and roof bolter in operation underground (Fourie *et al*., 2017a). The equipment is operated remotely, resulting in improvement in safety of the mining staff, since the operator is removed from the production face and separated from the machines (Harrison, 2008). Figure 6.4 (d) shows the narrow stoping environment at a typical underground platinum mine in South Africa (Fourie *et al*., 2014).

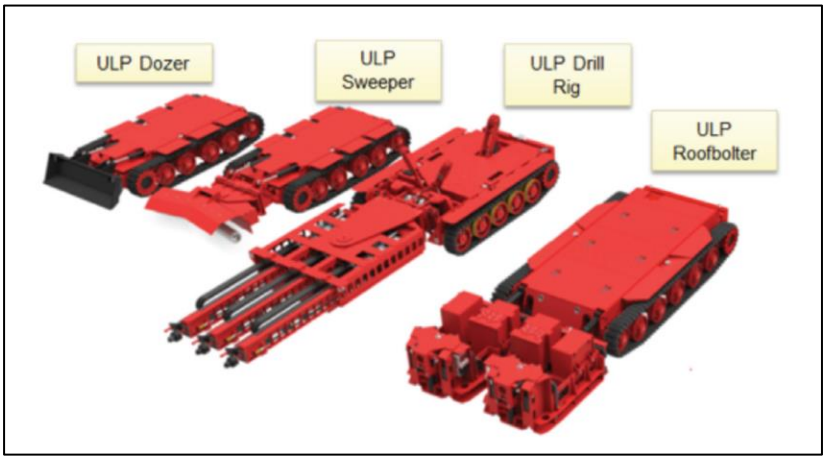

Figure 6.3 An example of a ULP fleet of equipment (Fourie *et al*., 2014)

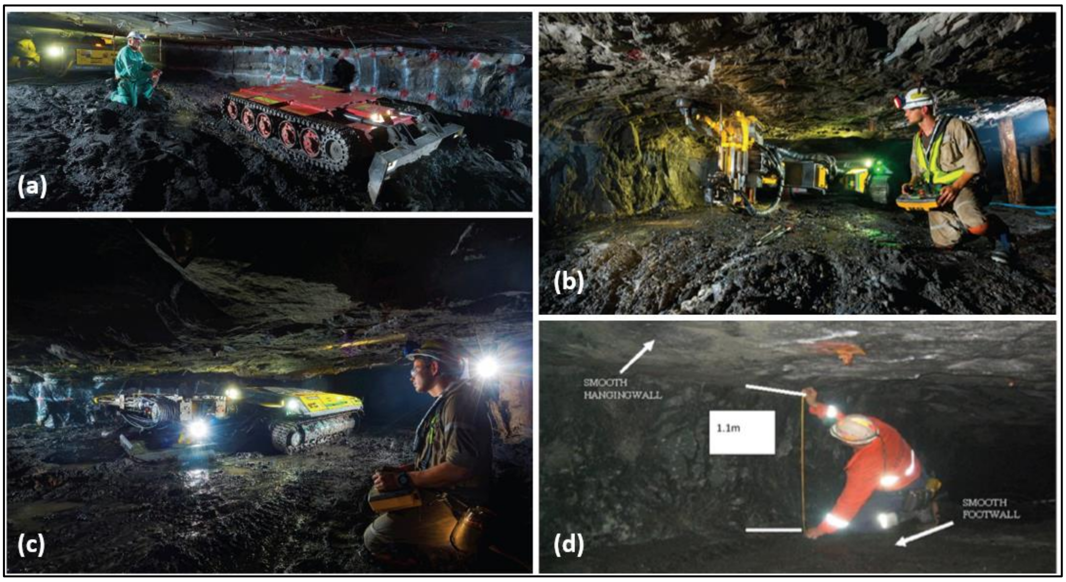

Figure 6.4 Application of XLP equipment underground (a-c) and the typical stoping width for narrow reef platinum mines (Fourie *et al*., 2014; Fourie *et al*., 2017a)

6.1.3 Hybrid mechanised mining

Often called large reef drive mechanisation, this method employs both conventional and mechanised mining elements (Egerton, 2004). Large reef drives are developed using mechanised equipment and then stoping is undertaken using labour-intensive conventional mining methods with manual drilling and cleaning (Egerton, 2004). Trackless equipment such as LHDs and trucks in large reef drives are used to load and tram the ore to the conveyor belt in the decline, for hauling to the surface (Egerton, 2004). Although stoping dilution is low, the shaft grade is marginally lower than that of conventional mining but higher than that of fully mechanised mining operations (Egerton, 2004). This is because of the waste dilution added by the large development excavations (Egerton, 2004). Ore throughput is higher than conventional mining methods and people and equipment can be more efficiently transported to the working areas (Egerton, 2004). Additionally, the large developments allow for improved ventilation flow (Egerton, 2004). Some of the disadvantages of this method include high initial capital requirements, increased ventilation costs due to diesel engines working in confined spaces, as well as potential safety hazards that could arise when people and large moving machinery must operate in the same working environment (Egerton, 2004).

6.1.4 Continuous mining using non-explosive rock breaking

The methods described in 5.1.1 to 5.1.3 are all cyclic methods that depend on the drilling and blasting cycle and hence a re-entry period is required before cleaning and hauling can take place (Pickering *et al.*, 2006). This limits the productivity, as during the re-entry period, all work stops, and the mine is evacuated to allow the blasting fumes and dust to clear. Lessons from the coal mining industry show that mining by means of rock cutting, as opposed to drilling and blasting, provides the opportunity for continuous mining operations because no re-entry period will be required as no blasting takes place (van den Berg, 2014; Vogt, 2016). In this mining method, rock cutting techniques are used for development as well as stoping (van den Berg, 2014). More time will be spent at the rock face and the operation will be less labour-intensive, potentially leading to higher productivity and profit margins (van den Berg, 2014). However, rock cutting is not extensively used in platinum mines because unlike coal, that is classified as low strength with a Uniaxial Compressive Strength (UCS) less than 25MPA, South African platinum reefs are classified as abrasive and high strength with a UCS between 50 MPA and 100 MPA (Vogt, 2016).

Some underground rock cutting techniques that have been trialled in the Bushveld Complex or for similar hard rock environments include disk cutting, reef boring, diamond wire cutting and undercutting (van den Berg, 2014). Since 2002, rock cutting has been trialled at Lonmin, Impala and Anglo American Platinum mining companies, and has yielded variable results with trials still on-going at some operations (Pickering *et al.*, 2006; van den Berg, 2014; Fraser, 2017). Figure 6.5 shows an example of a narrow reef hard rock continuous cutting machine developed by Caterpillar, capable of operating in the stope widths of 1.3 to 2 m. The cutter is electrically powered and uses activated undercutting technology to cut the rock (Killian, 2016). This system additionally has hydraulic roof support and hard rock chain conveyor, and is controlled by the long-wall automation system and is responsible for cutting, loading and hauling (Killian, 2016).

Rock cutting methods such as raise boring and tunnel boring are already successfully used in the platinum mining industry for large excavations such as shaft sinking, travelling ways and ventilation holes (van den Berg, 2014). However, there is no operational underground rock cutting platinum mine in South Africa. Other non-explosive rock breaking technologies that could be viable but are at their trial infancy are foam injection rock breaking, thermal spalling, and microwave drilling (Fraser, 2017).

Figure 6.5 a) Caterpillar (CAT) Rock Straight System - underground hard rock narrow reef cutting machine b) Underground control room with an operator controlling the CAT rock straight system c) CAT Rock Straight Hydraulic roof support (Caterpillar, 2016)

6.2 Quantification of Electricity and Water for Modern Mining Methods

In 2000, the Mining Association of Canada (MAC) commissioned a benchmarking study focused on energy consumption of mining and processing activities of underground bulk Canadian mines. Six base metal mines and five gold mines participated in the study and energy consumption data was collected of all mining cycle activities, processing and refinery plants (LCG Energy Management Group, 2009). Discounting the differences between orebody geometry and depths, most of these mines are highly mechanised and are accessed through declines that are designed to accommodate the movement of rock by heavy earth moving equipment (LCG Energy Management Group, 2009). The closest South African comparison to the mines in the study are fully mechanised underground mines with declines that accommodate large diesel machinery.

The cumulative energy intensity in percentage of all the underground activities is shown in Figure 6.6 (LCG Energy Management Group, 2009). The LCG Energy

Management Group (2009) case study shows an efficient approach to monitoring, comparing and reporting energy use for eleven different mining processes. It is also evident that mining method and ore body geology have huge impacts on energy consumption patterns (LCG Energy Management Group, 2009). LCG Energy Management Group (2009) found that ventilation requirements are the largest energy user (41.85% as shown in Figure 6.6) for the average mechanised mine and can be attributed to factors such as air required for human activities, underground temperature and the quality of diesel fuel used by equipment underground.

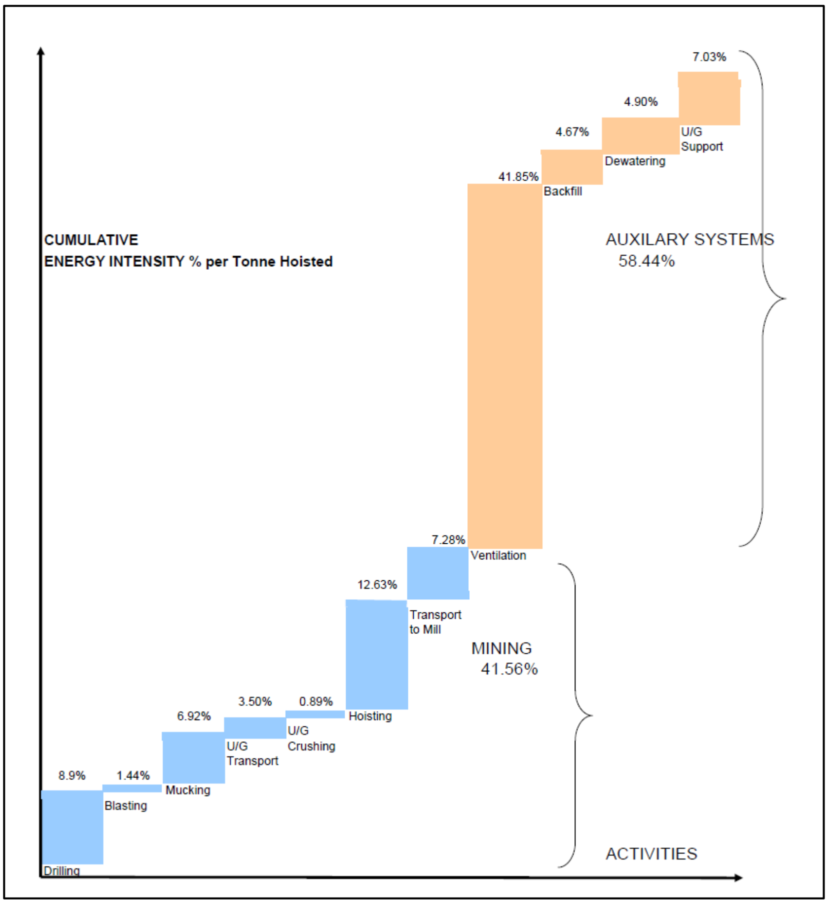

Figure 6.6 The average cumulative energy intensity percentage per tonne ore hoisted for various underground mining activities obtained from a study of Canadian mines (LCG Energy Management Group, 2009)

In XLP and ULP methods diesel, battery and trailing cable machinery are used to power the respective suites of equipment, with diesel-powered equipment characterised by the disadvantage of increasing the ventilation cost due to the underground emission control requirements (Valicek and Fourie, 2014). The trailing cable machinery relies on the electrical power drawn from the grid, which is clean and satisfies the equipment power requirements, but can pose an electric hazard if the cable is accidentally damaged or driven over and also has an impact on the mobility and productivity of the equipment (Valicek and Fourie, 2014). The use of lithium batteries to power the equipment provides a clean form of energy, with no emissions, but the low on-board energy storage and long recharge times have a negative impact on productivity (Valicek and Fourie, 2014).

Anglo American Platinum trialled the use of fuel cells in its narrow reef mining machinery (Valicek and Fourie, 2014). Fuel cell powered equipment will have sufficient on-board power, no emissions, will use no electrical power and will be more manoeuvrable and safer than the cable powered equipment (Valicek and Fourie, 2014). Ventilation and electricity requirements will be reduced and productivity increased (Valicek and Fourie, 2014). In addition, the use of fuel cell technology for underground mining machinery will increase the local demand for platinum (Valicek and Fourie, 2014). There is no published data quantifying the electricity savings that result from implementation of fuel cell and battery technology for ULP and XLP machinery.

Anglo American Platinum commissioned a study by the BBEnergy company at Anglo American Platinum's modernised conventional mining stope to analyse the performance of different drilling technologies, namely pneumatic, electric, hydro-powered and electro-hydraulic drills (Fourie *et al.*, 2017b). One of the aspects that the study focused on was energy and water consumption per panel per day of the different drills, with the results shown in Table 6.2. The electric, hydro-powered and electro-hydraulic drills used much less electricity per panel per day (less than 155 kWh/day/panel) compared to the pneumatic drill (that used 958 kWh/day/panel) (Fourie *et al.*, 2017b). This translates to approximately six-fold improvement in energy efficiency by not using the pneumatic drill (commonly used drill in current conventional mining operations). The total water consumption of the electric, hydro-powered and electro-hydraulic drills per panel is also less than that of the pneumatic drills. This represents a 23% water saving when comparing the pneumatic drill (the largest water consumer of the drills) to the electric drill (second largest water consumer of the drills). The study found that use of any of the three other drills, besides pneumatic drill, eliminates the need for compressed air and could result in decommissioning of expensive compressors (Fourie *et al.*, 2017b).

Table 6.2 A comparison of energy and water requirements for different rock drills

	Drill for Energy Medium Unit	Pneumatic Drill	Electric Drill	Hydro Powered Drill	AC HRD100 Hydraulic Drill
Total Energy Required (from surface)					
Power per drill required (from surface)	kW	63.10	2.40	20.80	13.80
No. of hours penetrating per day per drill	hrs/day	2.44	2.51	1.33	1.33
Drill Energy Required per panel	kWh/day/ panel	923.00	31.00	133.00	88.00
De-Watering Energy					
No. of hours penetrating per day per drill	hrs/day	2.44	2.51	1.33	1.33
No. of hours that drill uses water	hrs/day	4.00	4.00	1.33	4.00
Water consumption during penetration	l/s	0.13	0.12	1.00	0.20
Water consumption during non-penetration	l/s	0.13	0.12	-	-
Water Recirculation	%	0%	0%	65%	0%
Total water consumption per panel per day	l/day	11 232.00	8 640.00	6 703.00	3 830.00
Pump out energy (at 830m lift) per panel	kWh/day/ panel	35.00	27.00	21.00	12.00
Energy Cost per Panel					
Total Energy Required per panel	kWh/day/ panel	958.00	58.00	154.00	100.00
Average Megaflex cost per kWh	R/kWh	0.85	0.85	0.85	0.85
Energy Cost per Panel per day	Rand per day	815.00	49.00	131.00	85.00

Source: Fourie *et al.* (2017b)

Although not quantifiable due to a lack of detailed information, other technologies that were trialled at the test site also show evidence for increased energy and water efficiencies, which may be translated to energy and water cost savings. These are briefly discussed below (Fourie *et al.*, 2017b):

a) Charging: The use of improved explosives, for example, emulsion explosives that are being trialled at the modernised stope, may potentially improve blasting efficiencies and trialled fragmentation. This could result in energy efficiencies, as the improved fragmentation will improve the efficiency of other upstream activities such as cleaning, ore handling and comminution. This could also reduce the requirement for secondary blasting and result in potential energy savings at the processing plant;
b) Blasting: Throw blasting is also being trialled at the stope and is estimated to potentially throw 50% of the blasted material into the gulley, thus halving the volume of blasted material that needs to be cleaned. This could potentially result in improvements in cleaning efficiencies as cleaning cycle times will be reduced. An explosives management system is also being trialled and has the potential to enhance explosive efficiencies; and
c) Cleaning: The use of a waterjet is predicted to improve cleaning efficiencies, as it will replace face scraper winches.

6.3 Conclusion

Modernisation of the South African platinum mining industry need to take place to ensure long-term sustainability of the sector. This will include modernisation of the existing conventional mining operations, where the thickness of the reef will not allow for the implementation of fully mechanised mining and will include a focus on improvement in productivity and efficiency gains by introducing innovative technologies in the conventional stoping environment. Modernisation will further include the implementation of mechanised drill and blast mining methods, using LP, XLP and ULP technologies in the mines where the reef thickness would make it a viable business case. Modernisation may also include further research and testing of the technologies and platforms that would allow continuous autonomous mechanised mining by rock cutting or non-explosive rock breaking. It is important to note that the degree of modernisation of the South African platinum mining industry is dependent on factors such as orebody geometry (depth, dip, and width), rock strength, existing mining infrastructure, mineralogy and virgin rock temperature.

Little information is available in the public domain that provides a detailed overview of the water and energy consumption of current modernised underground platinum mines and how each activity contributes to the total energy or water consumption. This information would enable further understanding of the platinum mines' water and energy systems and further efficiency improvements across different mining activities for conventional, hybrid and mechanized mining operations. Current efficiency measures focus on benchmarking possible gains from the technological improvements in the specific energy or water intensive activity of the mining operations (for example, replacing pneumatic drills electro-hydraulic or electric drills).

7 COST IMPLICATIONS OF MODERN MINING METHODS ON ENERGY AND WATER CONSUMPTION FOR PLATINUM MINES

7.1 Introduction

Chapter 6 showed that there are various degrees of mine modernisation, constrained by various factors such as existing infrastructure, orebody geometry and virgin rock temperatures. Conventional operations can be modernised through improved efficiencies often enabled by the introduction of new technologies or processes. In Sections 6.1.1 and 6.2, examples of various modernisation trials at a "modernised conventional stope" of a conventional platinum mine were provided; however, at the time of writing, detailed information about the outcomes of most of the trials were confidential and were not available in the public domain. This study thus analysed results that were publicly available from the drilling trial in order to determine the cost implications, from a water and energy perspective, from modernising conventional operations through technological improvements.

The implementation of mechanised drill-and-blast and continuous non-explosive rock breaking mining methods is considered a form of modernisation. There are currently a few mechanised platinum mines that may be studied in order to determine the cost implications of modernising through mechanisation. With regards to future modern mining methods such as continuous non-explosive rock breaking, there are forecasts developed by the Minerals Council of South Africa of production estimates that could be yielded from the implementation of mechanisation and continuous rock breaking in platinum mines. These forecasts were used to estimate the energy and water consumption and the resulting cost implications for the industry associated with modernisation. The methodology and the analysis are detailed in Chapter 2. For all results and analysis, current conventional operations were used as a baseline.

7.2 Modern Conventional Mining

Anglo American Platinum trialled a few technologies at its conventional modernised stope test site Fourie *et al*., (2017b). Most of the results from this trial are confidential and not publicly available. A study was however published by Fourie *et al*., (2017b) with quantifiable results for the performance of drills at the trial site (discussed in Section 6.2), with water and energy consumption data presented in Table 6.2 for pneumatic, electric, hydro-powered and a light-weight hydraulic drill. Assuming that most conventional mines use pneumatic drills, pneumatic drills were used as a baseline for consumption and cost calculations.

Energy and water efficiencies and cost implications were calculated from the information presented by Fourie *et al*., (2017b) in Table 6.2 and the results are summarised in Table 7.1. Table 7.1 shows that by using an electro-hydraulic, hydro-powered and hydroelectric drills instead of a pneumatic drill, an energy consumption and cost reduction of between 84% and 94% can be achieved per panel per day. This amounts to a cost savings of between R 683.40 and R 765.00 per panel per day. Similarly, Table 7.1 shows that by using an electro-hydraulic, hydro-powered and hydroelectric drill instead of a pneumatic drill, a water reduction and cost saving of between 23% and 66% can be achieved per panel per day, amounting to water cost savings of between R 12.96 and R 37.01 per panel per day. Even though this was an isolated study using only one aspect of the mining cycle (drilling), this study demonstrates that the implementation of modern technologies could potentially have a significant impact on energy and water consumption that would subsequently translate to a significant reduction of costs for both water and energy.

Table 7.1 A comparison of the energy and water efficiencies for different drilling machines

	Pneumatic drill	Electric drill	Hydro-powered drill	AC HRD100 Hydraulic drill
Average water cost per panel per day (R) calculated by using an average Rand Water tariff for 2016/17 of R11.40/kl	128.05	98.45	76.41	43.66
Water cost reduction (R) compared to pneumatic drill water costs	-	29.60	51.64	84.39
Percentage reduction in water consumption and costs compared to pneumatic drill	-	23%	40%	66%
Average energy cost per panel per day (R) calculated by using an average megaflex tariff of R0.85/kWh (*Fourie et al.*, 2017b)	814.30	49.30	130.90	85.00
Energy cost reduction (R) compared to pneumatic drill energy costs	-	765.00	683.40	729.30
Percentage reduction in energy consumption and costs compared to pneumatic drill	-	94%	84%	90%

Source: Calculated using data from Fourie *et al.*, (2017b)

7.3 Mechanised Mining

Chapter 2 described the methodology, data sources, data collection process and data analysis used to establish the consumption and cost implications associated with extraction ore using mechanised operations instead of conventional operations. The sample data was from underground mining operations from Impala Platinum, Africa Rainbow Minerals and Northam Platinum. The sample size consisted of 17 underground mining operations.

The mining operations were characterised using the following criteria:

- Type of mining operation: Mining operations were classified as conventional or mechanised, based on the mining systems employed. Conventional mines are largely drill and blast operations. Some conventional mines have mechanised sections but still largely employ drill and blast mining methods and are thus classified as conventional operations. Mechanised mines mostly employ mechanised mining systems.

- Mining phase, namely growth, mature and old: Growth operations are sometimes referred to as expansion operations and are ramping up to desired capacity or are undertaking expansion plans. Mature operations are producing at a steady state. Old operations may be producing at a steady state or are heading towards decline as they approach the end of their life of mine.
- Mining depth: The mining depth is the depth of the deepest mine workings.
- Depth classification: Shallow operations are less than 1000m, intermediate operations are between 1000m and 2000m, and deep operations are greater than 2000m (Jager and Ryder, 1999). Mines at greater depths require more ventilation because of large cavity volumes that have to be ventilated at greater distances from the shaft. At some underground operations, ventilation fans operate 24 hours and seven days a week (ESKOM Demand Side Management Department, 2010). The depth of platinum mines also impacts the geothermal gradient and virgin rock temperatures at depths greater than 2 km can have virgin rock temperatures as high as 70°C in the Bushveld Complex (Minerals Council South Africa, 2017), thus resulting in greater cooling requirements.
- The presence of a refrigeration plant: Deep and intermediate platinum operations often require refrigeration plants to assist with cooling and ventilating the underground environment. The presence of a refrigeration plant will thus greatly increase electricity requirements and is thus an important consideration in this study.

Of the 17 mining operations, 3 were mechanised and 14 conventional. The mechanised operations were all shallow and, of the conventional operations, 8 were shallow and 6 were intermediate depth. Seven of the conventional operations were old, 4 were mature and 3 were in growth/ expansion phase. The mechanised operations were all mature. Eight of conventional intermediate operations had refrigeration plants. None of the shallow operations had refrigeration plants. Table 7.2 provides a summary of the characterisations of the mining operations used in the study. The annual energy and potable water consumption for each of the operations between 2013 to 2017 is presented in Appendix C.

Table 7.2 Summary of the characterisations of the mining operations in the study

Name	Type	Phase	Refrigeration	Mining depth	Depth classification
Operation 1	Conventional	Growth	Y	1650	Intermediate
Operation 2	Conventional	Mature	Y	11# - 966 11C - 1251	Intermediate
Operation 3	Conventional	Mature	Y	1180	Intermediate
Operation 4	Conventional	Old	Y	1126	Intermediate
Operation 5	Conventional	Growth	Y	1157	Intermediate
Operation 6	Conventional	Growth	Y	1063	Intermediate
Operation 7	Conventional	Mature	Y	961	Shallow
Operation 8	Conventional	Mature	Y	766	Shallow
Operation 9	Conventional	Old	N	688	Shallow
Operation 10	Conventional	Old	N	668	Shallow
Operation 11	Conventional	Old	N	496	Shallow
Operation 12	Conventional	Old	N	337	Shallow
Operation 13	Conventional	Old	N	257	Shallow
Operation 14	Conventional	Old	N	Decline shaft (195 m)	Shallow
Operation 15	Mechanised	Mature	N	450	Shallow
Operation 16	Mechanised	Mature	N	450	Shallow
Operation 17	Mechanised	Mature	N	450	Shallow

7.3.1 Unit energy consumption and cost implications

The annual unit energy consumption from 2013 to 2017 for each of the operations is shown in Figure 7.1 and the data is presented in Table D1 in Appendix D. The number of years over which the data was averaged is shown next to the operation number in Figure 7.1. Figure 7.1 shows that for the conventional operations, the unit energy consumption was highest in 2014. This was due to reduced production in 2014 because of a six-month labour strike that affected the Rustenburg platinum shafts. It is also noted that Operation 1 had a very high unit energy consumption in 2014, which reduced in subsequent years. The reason for this outlier is because the operation is a growth operation and was ramping up production. Generally, Figure 7.1 shows that the mechanised operations and some shallow operations were characterised by low unit energy consumption and showed very little variation over the five years. The intermediate conventional operations were the least energy efficient.

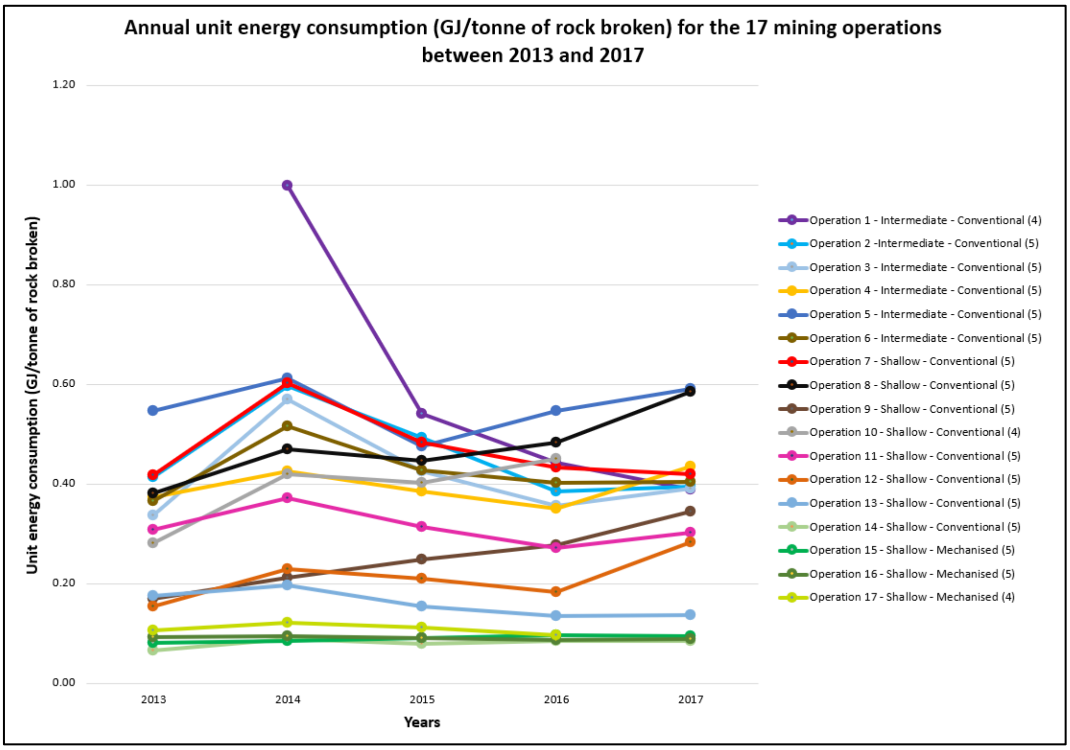

Figure 7.1 Annual unit energy consumption (GJ/tonne of rock broken) between 2013 to 2017

Figure 7.2 shows average unit energy consumption in GJ/tonne of rock broken, with the average production data overlaid. The data shown in Figure 7.2 is presented in Table D2 in Appendix D. The number of years over which the data was averaged is shown next to the operation number in Figure 7.2. From Figure 7.2 it is evident that the intermediate conventional operations were the most energy intensive. This is most likely attributed to the greater depth and distance of the working places from the shaft, resulting in greater ventilation, cooling and pumping requirements. Eight of the ten intermediate conventional operations have refrigeration plants as indicated in Table 7.2. Other contributing factors for low energy efficiency might be aged infrastructure such as ventilation, water and air reticulation systems that are often associated with leakages and losses. Additionally, the use of pneumatic powered drills, used in most conventional mines, was shown by Fourie *et al.*, (2017b) in Section 6.2 to be inefficient and energy intensive.

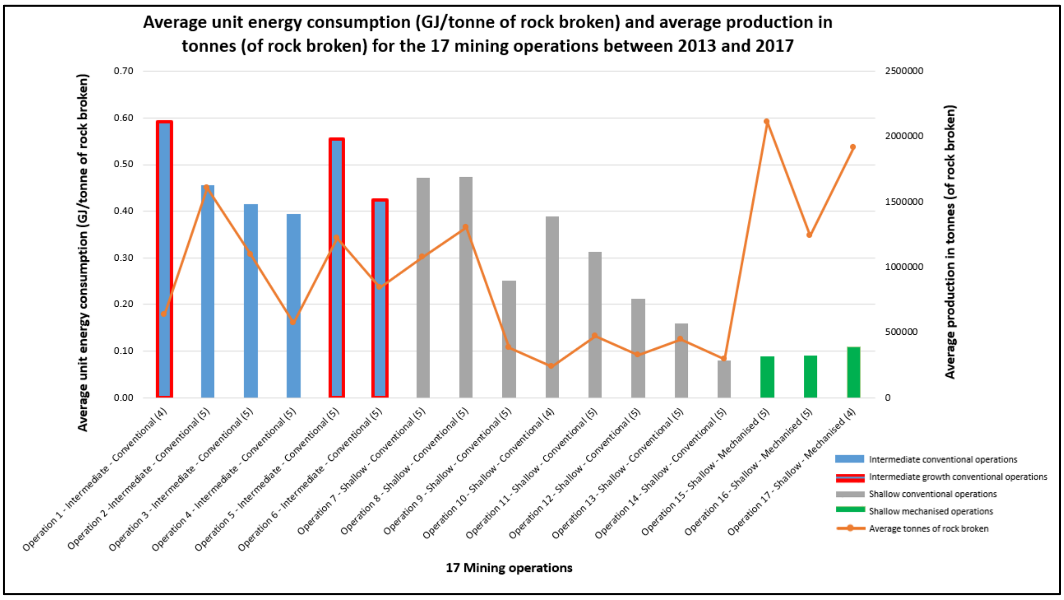

Figure 7.2 Average unit energy consumption (GJ/tonne of rock broken) and average production in tonnes (of rock broken) between 2013 to 2017

The unit energy consumption for conventional operations ranged between 0.08 and 0.59 GJ/tonne of rock broken. The average unit energy consumption for the intermediate conventional operations was 0.47 GJ/ tonne of rock broken. The shallow operations (conventional and mechanised) consume less energy per tonne than their deeper counterparts. However, the mechanised operations were not only energy efficient, but were also characterised by the highest production throughput. The shallow conventional operations had an average unit energy consumption of 0.29 GJ/ tonne of rock broken, whilst the shallow conventional operations with a similar depth (195 m to 496 m), refrigeration and phase profile to the mechanised operations had an average unit energy consumption of 0.19 GJ/ tonne. The average unit energy consumption for all conventional operations was 0.37 GJ/tonne. The unit energy consumption for the mechanised operations ranged between 0.09 and 0.11 GJ/tonne of rock broken. The mechanised operations had an average unit energy consumption of 0.1 GJ/ tonne of rock broken. These results are summarised in Table 7.3. From these results, by comparing the average energy consumption of the conventional operations with a similar depth, refrigeration and phase profile as the mechanised operations, the mechanised operations used approximately 47% less energy to mine a tonne of rock than similar conventional operations.

Table 7.3 Summary of the average unit energy consumption (GJ/tonne of rock broken) for the platinum operations

Mining Operations	**Number of years over which data was averaged**	**Average unit energy consumption (GJ/tonne of rock broken)**
Shallow conventional operations	8	0.29
Intermediate conventional operations	6	0.47
All conventional operations	14	0.37
Shallow conventional operations with depth from 195 m to 496 m	4	0.19
Shallow mechanised operations	3	0.10

Figure 7.3 shows the relationship between unit energy consumption and depth on a bubble plot, with the size of the bubble denoting production tonnes. The data shown Figure 7.3 is presented in Table D3 in Appendix D. For conventional operations at shallow depths, Figure 7.3 shows a linear proportional relationship between unit energy consumption and depth for the conventional operations. As the depth increases, the average energy consumption per tonne of rock broken also increases. It is not possible to observe a relationship between unit energy

consumption and depth for the mechanised operations since they are all at the same depth.

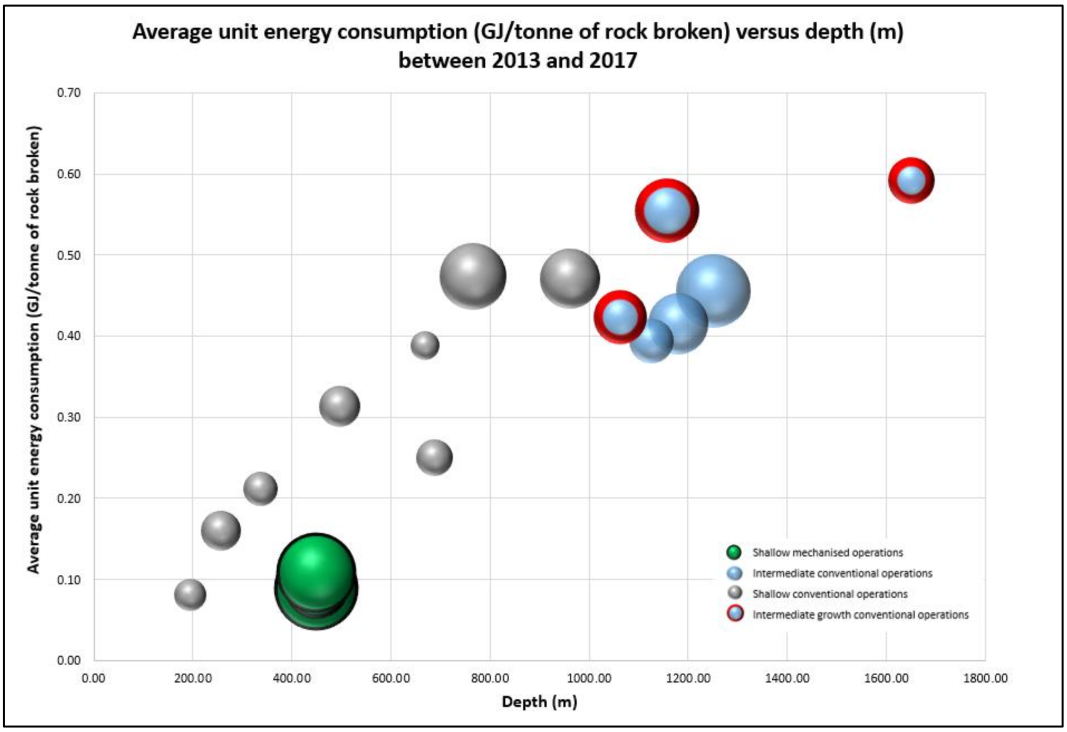

Figure 7.3 Average unit energy consumption (GJ/tonne of rock broken) and depth (m) between 2013 to 2017. The size of the bubble denotes the average production in tonnes (of rock broken)

Motiang (2018) compiled the annual average ESKOM prices (in c/kWh) paid by various customer categories between 2008 and 2017 from ESKOM statistical yearbooks and annual reports. The prices are applicable to customers who purchase electricity directly from ESKOM and exclude VAT. The average annual prices between 2013 and 2017 that were charged to mining customers are shown in Table 7.4.

Table 7.4 Average annual ESKOM electricity tariffs (c/kWh) for the mining industry

Year	Annual average ESKOM prices (c/kWh)
2013	64.66
2014	69.52
2015	78.01
2016	84.8
2017	86.91

Source: Motiang (2018)

Using these average prices and the average electricity consumption in kWh, the annual average unit electricity costs between 2013 and 2017 were calculated for each mining operation. These yearly cost results are presented in Table D4 in Appendix D and were used to calculate the average unit electricity costs for each of the mining operations.

Figure 7.4 shows the average unit electricity costs for each mining operation over the data range between 2013 and 2017. The data shown Figure 7.4 is presented in Table D5 in Appendix D. The number of years over which the data was averaged is shown next to the operation number in Figure 7.4. Figure 7.4 shows that intermediate conventional operations spent more for electricity per tonne of rock broken. Six of the eight shallow conventional operations spent less on average for electricity per tonne of rock broken compared to their deeper counterparts. Mechanised operations spent the lowest on electricity costs to break a tonne of rock.

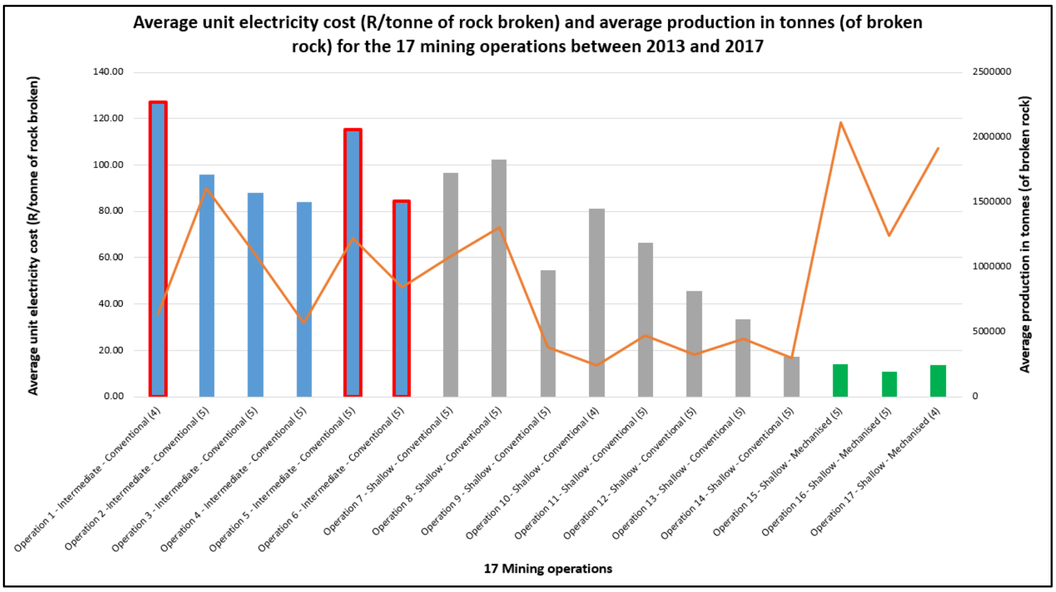

Figure 7.4 Average unit electricity cost (R/tonne of rock broken) and average production in tonnes (of broken rock) between 2013 and 2017

The unit electricity costs ranged between R 17 and R 127 per tonne of rock broken for the conventional operations and between R 11 and R 14 per tonne of rock broken for mechanised operations. The average unit electricity costs were R 99/tonne of rock broken for the intermediate conventional operations, R 62/tonne of rock broken for the shallow operations, and R 13/tonne of rock broken for the mechanised operations. Shallow conventional mines with a similar depth (195 m to 496 m), refrigeration and phase profile to the mechanised operations spent an average of R 40/tonne of rock broken on electricity. These results are summarised in Table 7.5. From these results, by comparing the average energy consumption of the conventional operations with a similar depth, refrigeration and phase profile as the mechanised operations, the mechanised operations spent R27 less per tonne of rock broken, equivalent to a cost saving of 67.5%.

Table 7.5 Summary of the average unit electricity costs (R/tonne of rock broken) for the platinum operations

Mining Operations	Number of years over which data was averaged	Average unit electricity costs (R/tonne of rock broken)
Shallow conventional operations	8	62
Intermediate conventional operations	6	99
All conventional operations	14	78
Shallow conventional operations with depth from 195 m to 496 m	4	40
Shallow mechanised operations	3	13

7.3.2 Unit potable water consumption and cost implications

The annual unit potable water consumption for each of the operations is shown in Figure 7.5 and the data is presented in Table D6 in Appendix D. The number of years over which the data was averaged is shown next to the shaft number in Figure 7.5. Similar to the unit energy consumption, Figure 7.5 shows that low production in 2014 (due to the six-month labour strike) also impacted the unit potable water consumption. Operation 1 had a very high unit potable water consumption in 2014, that reduced in subsequent years. This outlier is a growth operation and was ramping up in production. From Figure 7.5 it is evident that the mechanised operations were characterised by low unit potable water consumption and showed very little variation over the five years. The conventional operations show greater variability over the five-year period and had a higher unit potable water consumption.

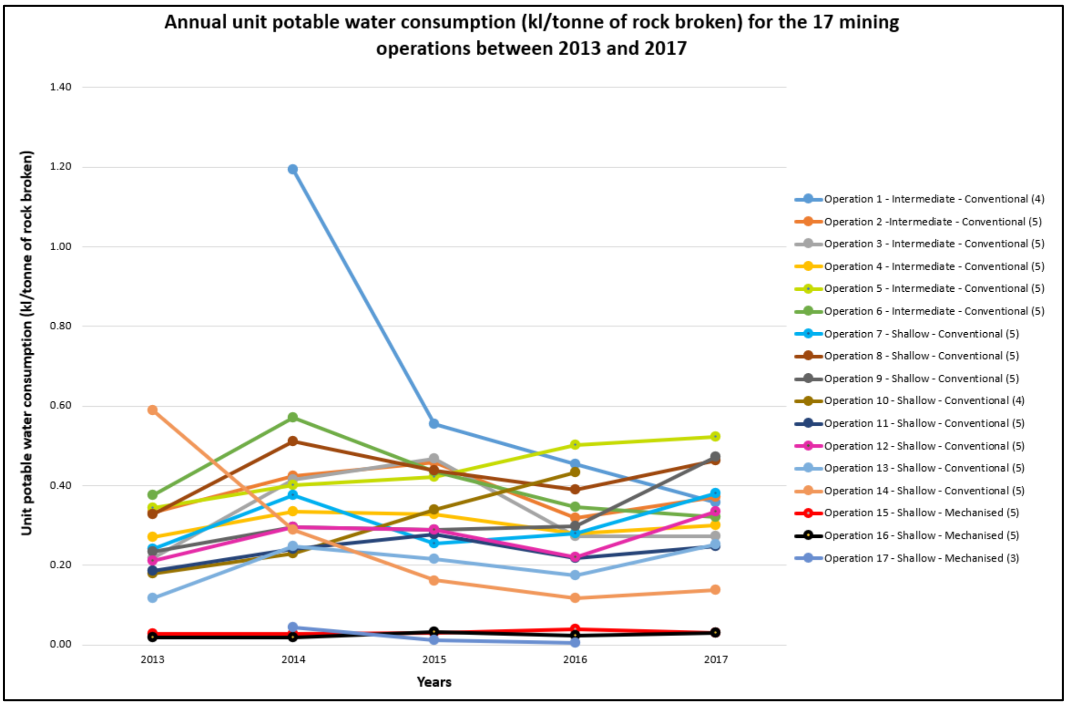

Figure 7.5 Annual unit potable water consumption (kl/tonne of rock broken) between 2013 to 2017

Figure 7.6 shows the average unit potable water consumption in kl/tonne of rock broken, with the average production data overlaid. The data shown Figure 7.6 is presented in Table D7 in Appendix D. The number of years over which the data was averaged is shown next to the shaft number in Figure 7.6. Similar to the energy consumption patterns, the graph indicates that the intermediate conventional operations were water intensive. Similar to the unit energy consumption, the mechanised operations not only had the lowest unit potable water consumption but were also characterised by the highest production throughput. The conventional operations in the study are more labour-intensive compared to the mechanised operations and thus have more employees underground that would require more potable water for drinking purposes. Additionally, aging infrastructure in conventional operations may result in water pipe leakages, and consequently and increase in potable water consumption.

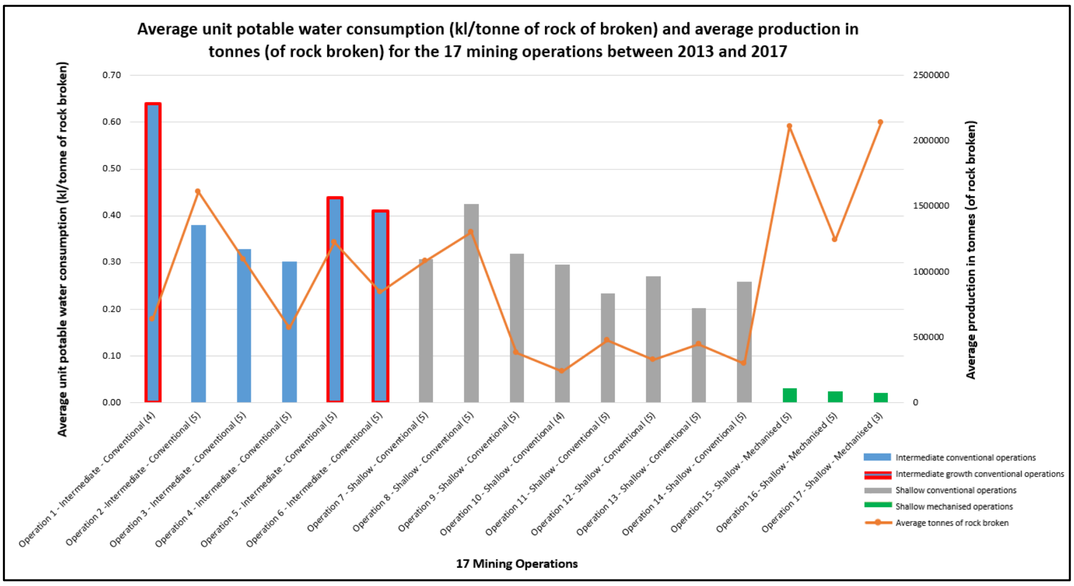

Figure 7.6 Average unit potable water consumption (kl/tonne of rock broken) and average production in tonnes (of rock broken) between 2013 to 2017

The unit potable water consumption for conventional operations ranged between 0.20 and 0.64 kl/tonne of rock broken. The average unit potable water consumption was 0.42 kl/ tonne of rock broken for the intermediate conventional operations, 0.29 kl/ tonne of rock broken for the shallow conventional operations and 0.34 kl/ tonne of rock broken for all the conventional operations. The unit potable water consumption for the mechanised operations ranged between 0.02 and 0.03 kl/tonne of rock broken, with an average of 0.03 kl/ tonne of rock broken. The shallow conventional operations with a similar depth (195 m to 496 m), refrigeration and phase profile to the mechanised operations had an average unit potable water consumption of 0.24 kl/ tonne of rock broken. These results are summarised in Table 7.6. From these results, by comparing the average unit potable water consumption of the conventional operations with a similar depth, refrigeration and phase profile as the mechanised operations, the mechanised operations required approximately 87% less potable water to mine a tonne of rock than the similar conventional operations.

Table 7.6 Summary of the average unit potable water consumption for the platinum operations

Mining Operations	Number of years over which data was averaged	Average unit potable water consumption (kl/ tonne of rock broken)
Shallow conventional operations	8	0.29
Intermediate conventional operations	6	0.42
All conventional operations	14	0.34
Shallow conventional operations with depth from 195 m to 496 m	4	0.24
Shallow mechanised operations	3	0.03

Figure 7.7 shows the relationship between unit potable water consumption and depth on a bubble plot, with the size of the bubble denoting production tonnes. The data shown Figure 7.7 is presented in Table D8 in Appendix D. Figure 7.7 indicates a linear relationship between unit potable water consumption and depth for conventional operations. As the depth increased, the potable water consumption per tonne of rock broken also increased. The mechanised operations are however outliers on the graph and show a much lower unit potable water consumption compared to the conventional operations. There is no observed relationship between unit potable water consumption and depth for the mechanised operations because they are all at the same depth.

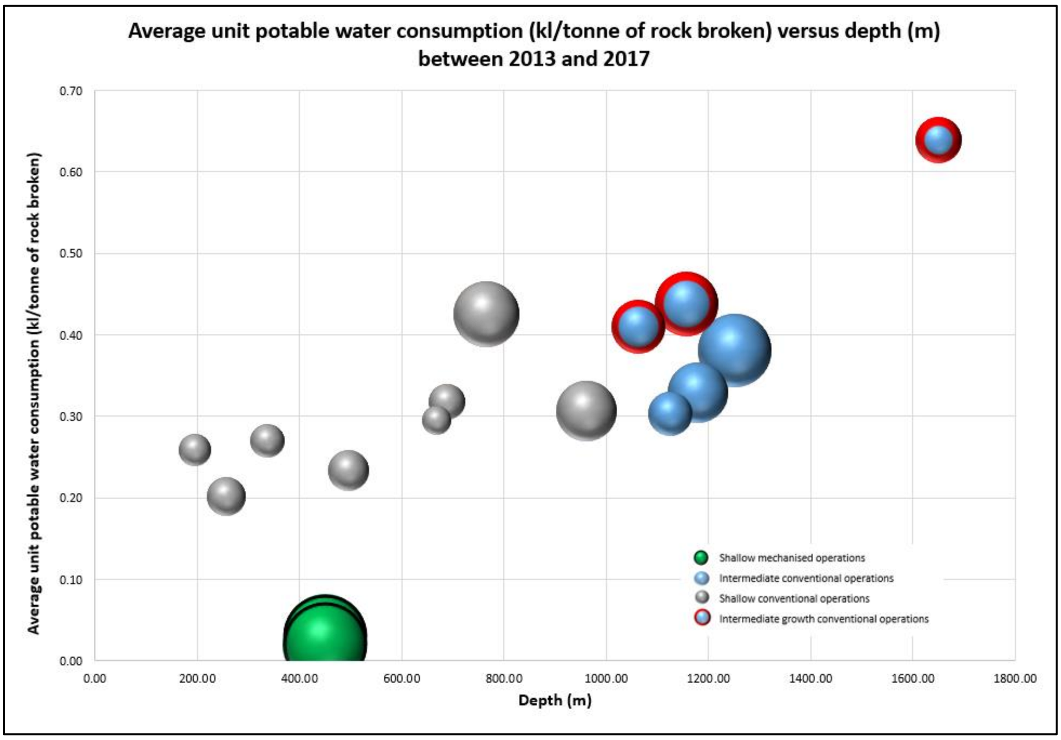

Figure 7.7 Average unit potable water consumption (kl/tonne of rock broken) and depth (m). The size of the bubble denotes the average production in tonnes (of rock broken)

Water tariffs are variable, unpredictable and complex and differ broadly based on supply areas (Water Research Council, n.d.). There are many factors considered in water tariff price setting such as water infrastructure charges, water connection fees, fixed and volume related charges, the geographical location of the municipality water is purchased from, distances to water resources, the season and the consumer characteristics (Water Research Council, n.d.). The location of mines, the waste discharge and the type of mining also plays a significant role in the water tariffs the mines will pay (Water Research Council, n.d.).

For this study, potable water tariffs were only available for the conventional operations based in Rustenburg. The conventional operations in the study purchase potable water from Rand Water. The annual Rand Water potable water tariffs for 2013 to 2017 are presented in Table 7.7. Potable water tariffs for the mechanised operations were not available as these were considered sensitive business information. The mines situated in the Burgersfort and the Greater Tubatse municipality (where the mechanised operations are located) purchase water in bulk from the Lebalelo water scheme and not the municipality. At the time of writing, however, the scheme tariffs were also not publicly available. In the absence water information for the mechanised operations, the Rand Water tariffs were used for all the mines in the study.

Table 7.7 Annual Rand Water potable water tariffs (R/kl) between 2013 and 2017

Year	Annual Rand Water potable water tariffs (R/kl)
2013	7.57
2014	8.98
2015	10.19
2016	11.40
2017	12.56

Using these average potable water tariffs and the average potable water consumption in kWh, the annual average unit potable water costs were calculated for each of the mining operations between 2013 and 2017. These annual potable water cost for each of the mining operations are presented in Table D9 in Appendix D and were used to estimate the average unit potable water costs for each mining operation. Figure 7.8 shows the average unit electricity costs for each operation over the data range between 2013 and 2017. The data shown Figure 7.8 is presented in Table D10 in Appendix D. The number of years over which the data was averaged is shown next to the operation number in Figure 7.8. Figure 7.8 shows that conventional operations spent more on potable water per tonne of rock broken than the mechanised operations.

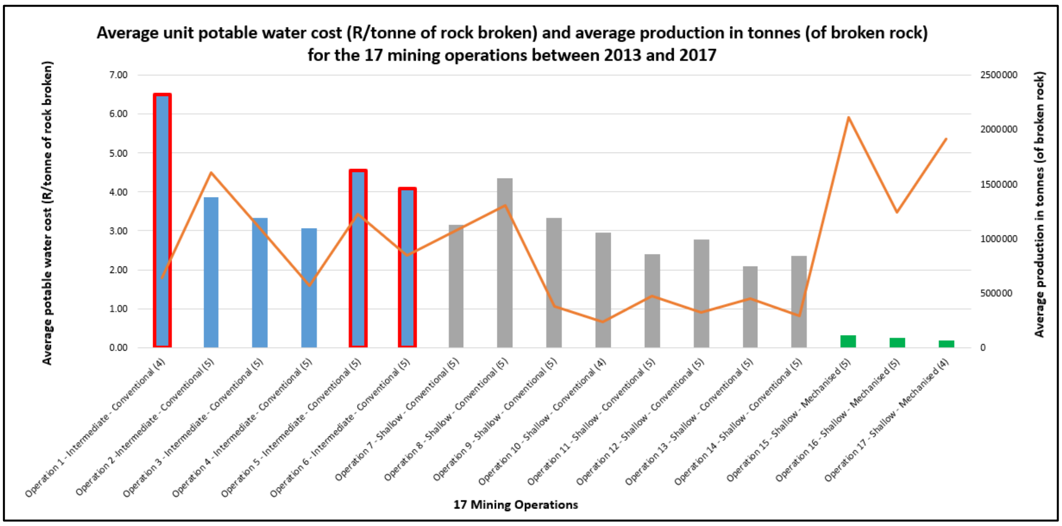

Figure 7.8 Average unit potable water costs (R/tonne of rock broken) and average production in tonnes (of broken rock) between 2013 and 2017

The unit potable water costs ranged between R 2.09 and R 6.51 per tonne of rock broken for the conventional operations and R 0.19 and R 0.31 per tonne of rock broken for mechanised operations. The average unit potable water costs were R4.23 /tonne of rock broken for the intermediate conventional operations, R2.93 / tonne of rock broken for the shallow operations, and R0.25 /tonne of rock broken for the mechanised operations. Shallow conventional mines with a similar depth (195 m to 496 m), refrigeration and phase profile to the mechanised operations spent an average of R2.41 /tonne of rock broken on potable water. These results are summarised in Table 7.8. From these results, by comparing the average energy consumption of the conventional operations with a similar depth, refrigeration and phase profile as the mechanised operations, the mechanised operations spent R2.16 less per tonne of rock broken, equivalent to a cost saving of 90%.

Table 7.8 Summary of the average unit potable water costs (R/tonne of rock broken) for the platinum operations

Mining Operations	Number of years over which data was averaged	Average unit potable water costs (R/tonne of rock broken)
Shallow conventional operations	8	2.93
Intermediate conventional operations	6	4.23
All conventional operations	14	3.49
Shallow conventional operations with depth from 195 m to 496 m	4	2.41
Shallow mechanised operations	3	0.25

7.4 Future Energy and Potable Water Demand and Potential Cost Implications for the Platinum Mining Industry

The predicted platinum payable reserves that will be unlocked as a result of the implementation of modern mining methods were modelled by the Minerals Council of South Africa and is shown in Figure 1.8 (Rupprecht, 2017; Fourie *et al.*, 2017a). This is currently the best available knowledge of future modern mining methods in the platinum industry. In this study, the assuming was made that continuous modern mining operations will consume, at most, the same unit energy and unit potable water consumption as current mechanised operations, hence both were referred to as mechanised operations.

7.4.1 Future energy demand and cost implications

The average unit energy consumption estimated in Section 7.3.1 was 0.37 GJ per tonne of rock broken for all conventional operations and 0.10 GJ per tonne of rock broken for all mechanised operations. Using these average unit energy consumption estimates and the forecasted production values presented in Table D11 in Appendix D (translated from Figure 1.8), the total energy (electricity and diesel) consumption forecast for the platinum sector was calculated. The results of this forecast are shown in Figure 7.9 and are presented in Table D12 in Appendix D. The forecasted production is correlated to the forecasted energy consumption because energy consumption is directly driven by the tonnages produced.

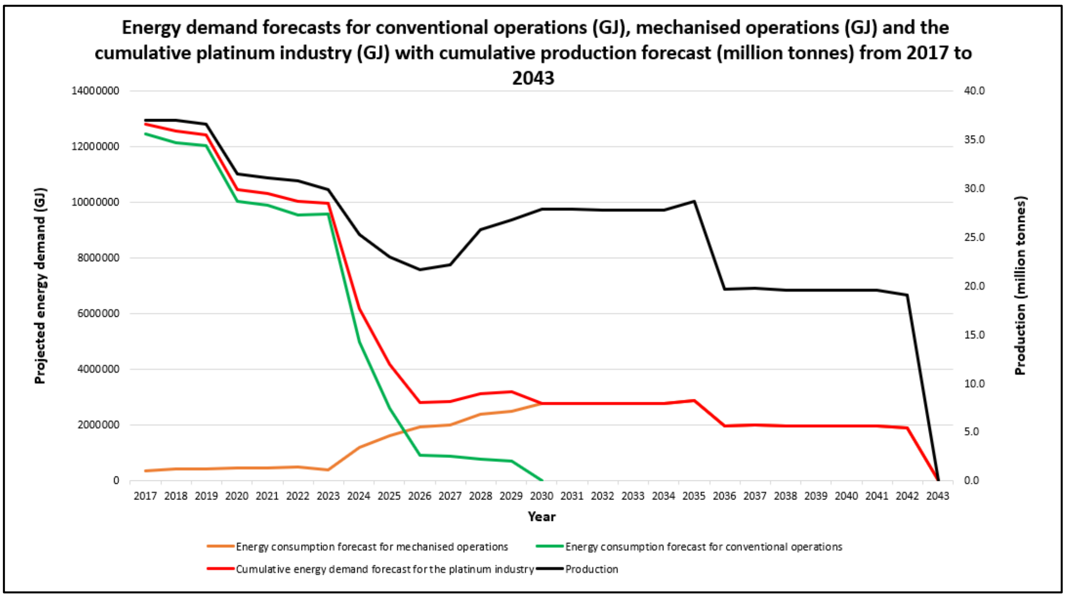

Figure 7.9 Energy demand forecasts for conventional operations (GJ), mechanised operations (GJ) and the cumulative platinum industry (GJ) with cumulative production forecast (million tonnes) from 2017 to 2043

In March 2011, the Department of Energy (2019) developed an integrated resource plan for 2010 to 2030 to ensure the security of electricity supply for South Africa, to reduce future electricity tariffs, to reduce water consumption in the process of generating electricity and to minimise environmental externalities such as carbon emissions. This strategy was developed to support South Africa's National Development Plan and was envisaged to be dynamic with frequent updates by the Department of Energy. The subsequent 2018 draft update extended the forecast from the year 2030 to 2050 and included various input assumptions, a plausible base-case, and various scenarios (Department of Energy, 2019). The updated forecasts were modelled based on a least-cost path (Department of Energy, 2019). The scenarios included demand forecasts, the implementation of unconstrained renewable energy, a carbon budget to reduce carbon emissions and varying gas tariffs. Tariff forecasts were modelled for five scenarios and these are shown in Figure 7.10. For this study the tariff path IRP7 (with a carbon budget and market-linked gas price) was digitised and used as the electricity price forecast. This is the worst-case scenario and resulted in the highest tariffs because it was based on a high coal and nuclear component in the generation mix (Department of Energy, 2019).

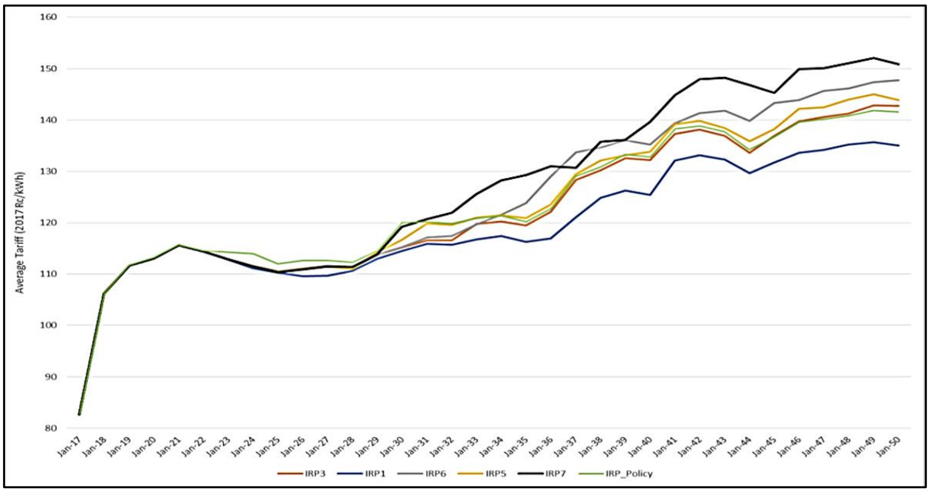

Figure 7.10 Various electricity tariff scenarios (Rc/kWh) from the 2018 updated Integrated Resource Plan (Department of Energy, 2019)

Using the energy forecast results shown in Figure 7.9 and presented in Table D12 in Appendix D, the digitised worse-case scenario electricity tariff forecast from the Department of Energy (2019) and the average percentage electricity consumed by conventional and mechanised operations, the total electricity cost forecast for the platinum sector was estimated. The average electricity-diesel split was estimated from the operations that provided electricity and diesel consumption data and was 97% electricity consumption and 3% diesel consumption for the conventional operations and 55% electricity consumption and 45% diesel consumption for the mechanised operations. The results of this cost forecast are shown in Figure 7.11 and is presented in Table D13. Figure 7.11 shows that the platinum industry will spend much more for electricity whilst conventional operations are used to extract platinum ores. Figure 7.11 shows that with the phasing out of conventional operations to mechanised operations, the platinum industry's electricity consumption will decrease from an average of 3000 GWh to an average of approximately 500 GWh per year. Consequently, the platinum industry will spend substantially less on electricity, from an average of R 3 billion per year to R 500 million per year, even with the envisaged electricity tariff increases.

From these electricity consumption and cost forecasts, it is inferred that, from the best available knowledge about the potential implementation of modernisation of the platinum industry as predicted in Figure 1.8, the platinum mining sector will significantly reduce its electricity consumption and consequently, reduce its electricity costs. With electricity costs representing a large portion of a mines energy and input costs and considering the high predicted electricity price increases and increasing electricity insecurities, the move to modernisation will potentially reduce energy consumption and costs for the platinum mining industry.

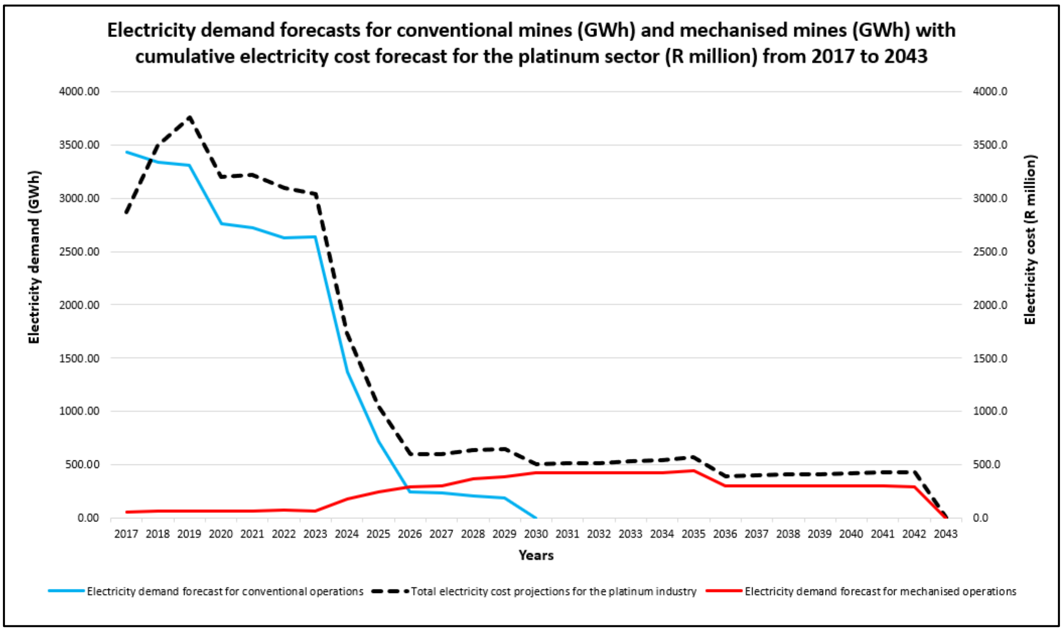

Figure 7.11 Electricity demand forecasts for conventional mines (GWh) and mechanised mines (GWh) with cumulative electricity cost forecast for the platinum sector (R million) from 2017 to 2043

7.4.2 Future potable water demand and cost implications

The average unit potable water consumption estimated in Section 7.3.2 was 0.34 kl per tonne of rock broken for conventional mines and 0.03 kl per tonne of rock broken for mechanised mines. Using these average unit potable water consumption estimates and the forecasted production values from in Table D11 in Appendix D (translated from Figure 1.8), the total potable water consumption forecast for the platinum sector was calculated. The results of this forecast are shown in Figure 7.12 and are presented in Table D14 in Appendix D. The forecasted production is correlated to the forecasted potable water consumption because water consumption is directly driven by the tonnages produced.

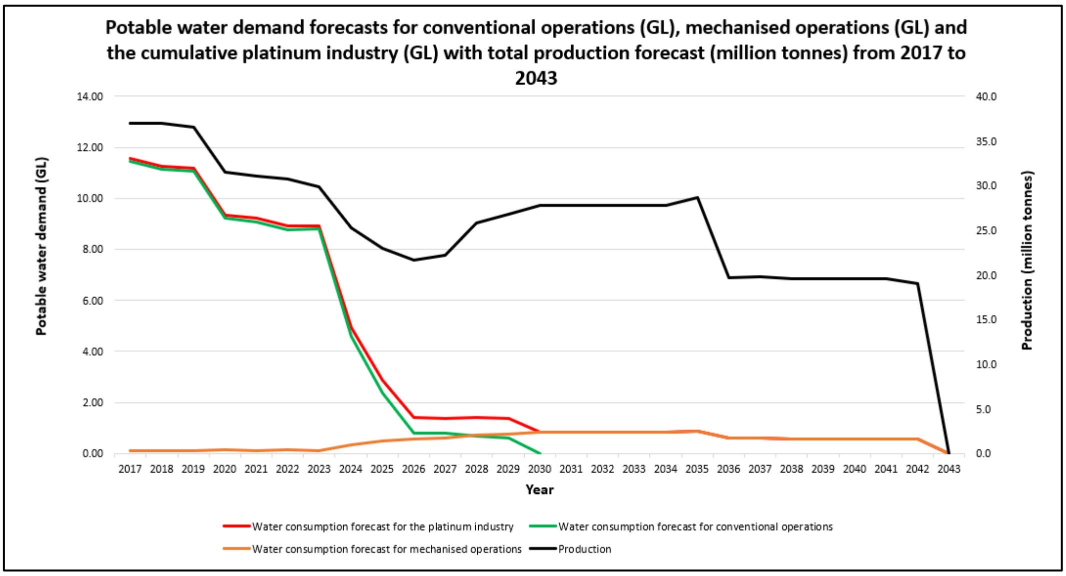

Figure 7.12 Potable water demand forecasts for conventional mines (GL), mechanised mines (GL) and the platinum sector (GL) from 2017 to 2043

At the time of writing, there were no publicly available potable water tariff forecasts because of the complexities associated with water tariff setting. To overcome this limitation, the potable water tariff information charged by Rand Water to mining clients from 2008 to 2017 was thus extrapolated linearly to 2043. The results of this extrapolation are shown in Figure 7.13 and is presented in Table D15. In light of continued draughts and water scarcity in South Africa, it is unlikely that potable water tariffs will continue to increase linearly, however, due to the complexity of tariff setting and prediction, at the time of writing this was the best available knowledge of potable water tariff forecasts.

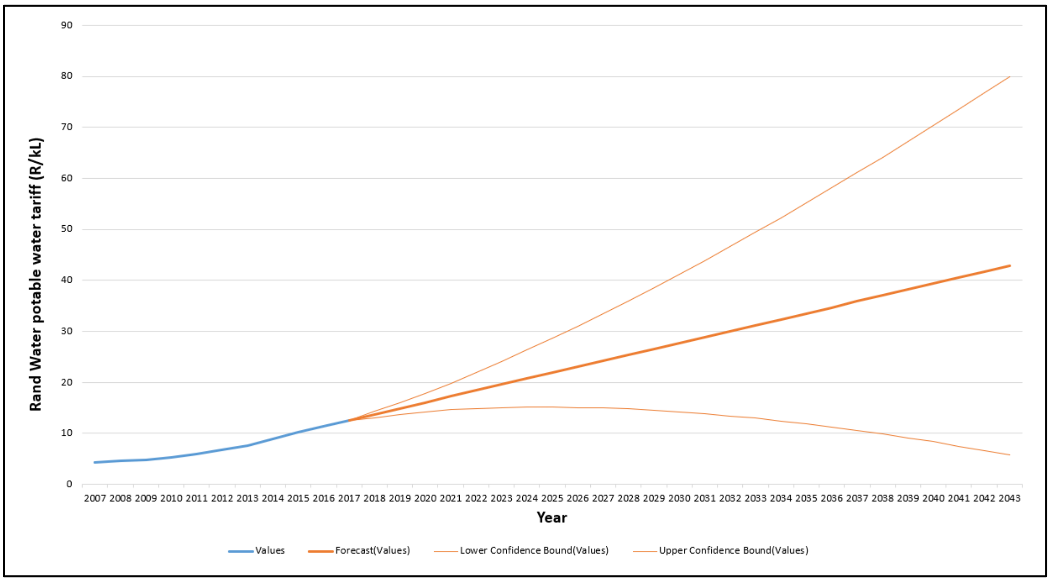

Figure 7.13 Linearly extrapolated potable water tariffs based on Rand Water prices from 2007 to 2017 (R/kl)

The total potable water cost forecast for the platinum sector was estimated using the potable water demand forecast shown in Figure 7.12 and presented in Table D14 in Appendix D and the linearly extrapolated Rand Water tariff forecast shown in Figure 7.13 and presented in Table D15. The results of this cost forecast is shown in Figure 7.14 and is presented in Table D16. Figure 7.13 shows that the platinum industry will spend much more for potable water whilst conventional operations are used to extract platinum ores. Figure 7.13 further shows that with the phasing out of conventional operations to mechanised operations, the platinum industry's potable water consumption will decrease from an average of 9 GL per year to approximately 1 GL per year. Consequently, the platinum industry will spend substantially less on potable water, from an average of ~R 160 million per year to ~R 30 million per year. From these potable water consumption and cost forecasts, it is evident that, from the best available knowledge about the potential implementation of modernisation of the platinum industry as predicted in Figure 1.8, the platinum mining sector will significantly reduce its potable water consumption and consequently, reduce its water costs. This would be favourable considering increasing water scarcity, water insecurities and increasing industrial competition for limited water resources.

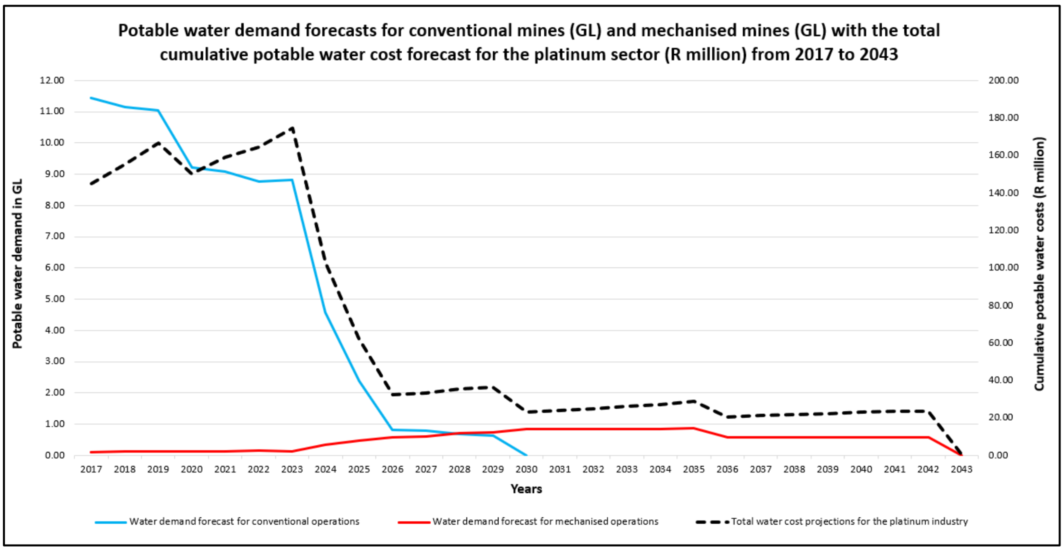

Figure 7.14 Potable water demand forecasts for conventional mines (GL) and mechanised mines (GL) with cumulative potable water cost forecast for the platinum sector (R million) from 2017 to 2043

7.5 Conclusion

Three scenarios were considered in this case study to establish the implications with respect to water and energy associated with the modernisation of the platinum mining industry, namely modernisation of conventional operations, modernisation through mechanised operations and future modernisation through the implementation of continuous mechanised operations.

To establish the consumption and cost implications of modernising conventional operations, the potential for modern mines to improve energy and water efficiencies through technological improvements such as the replacement of pneumatic drills with modern drills was shown in Fourie *et al*., (2017b). Further analysis of results obtained in Fourie *et al*., (2017b) showed that energy efficiency gains of between 84% and 94% per panel per day and subsequent cost saving of between R 683.40 and R 765.00 per panel per day was achieved. Water efficiency gains of between 24% and 66% per panel per day and subsequent cost saving of between R 12.96 and R37.01 per panel per day was achieved. Although not quantifiable due to confidentiality of the data, it is inferred that by modernising other activities of the conventional mining cycle, energy and water efficiencies are likely to improve.

To establish the consumption and cost implications of extracting ore from mechanised operations as opposed to conventional operations, 4 to 5 years of energy and potable water consumption data between 2013 and 2017 from conventional and mechanised operations was analysed. The range of the unit energy consumption for the mining operations was between 0.08 and 0.59 GJ/tonne of rock broken for conventional operations and between 0.09 and 0.11 GJ/tonne of rock broken for mechanised operations. These results are comparable to the unit energy consumption values from Bleiwas (2011), Tshikedi (2009) and Glaister and Mudd (2010), presented in Table 4.5. The average unit energy for conventional and mechanised operations are summarised in Table 7.3.

The range of the unit potable water consumption for the mining operations was between 0.20 and 0.64 kl/tonne of rock broken for conventional operations and between 0.02 and 0.03 kl/tonne of rock broken for mechanised operations. These results are substantially less than the unit water consumption values from Glaister and Mudd (2010), presented in Table 5.2, because this study only considered potable water and not bulk water. The average unit potable water consumption for conventional and mechanised operations are summarised in Table 7.6.

Mechanised operations were compared to shallow operations with a similar depth, refrigeration and phase profile. The mechanised operations consumed 47% less energy per of tonne of rock broken and spent R27 less on electricity per of tonne of rock (equivalent to a cost saving of 67.5%). With regards to potable water, the mechanised operations consumed 87% less potable water per of tonne of rock broken and R 2.16 less on potable water to per tonne of rock broken (equivalent to a cost saving of 90%). The average unit energy and potable water costs for conventional and mechanised operations are summarised in Table 7.5 and Table 7.8.

To establish the potential impact of future modernised operations on the platinum industry's water and energy consumption, water and energy consumption and cost forecasts were estimated. The energy and water demand forecasts further indicate that the implementation of modernised mining methods, mostly mechanised mining methods, will have a significant impact on the platinum industry's energy and water consumption and subsequent costs. Considering the uncertainty related to the future electricity costs and availability as well as increasing water scarcity being faced by South Africa, these increased water and energy efficiencies could potentially reduce environmental footprint of the platinum industry as well as improve profitability of the sector.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This study found that for the platinum mining industry, the intent is to modernise the industry by modernising conventional operations through the implementation of improved processes and modern technologies or where possible to extract platinum reefs through mechanised or continuous mechanised mining operations. The study showed that these modern mining operations will use less water and energy per tonne of rock broken compared to current conventional hard rock narrow reef mining methods. Where the geology permits, mechanised mining methods will be preferred due to associated benefits such as higher productivity and better energy and water efficiency. In cases where mechanisation will not be feasible due to geological constraints, modernised conventional mining methods should be adopted.

To support and reach this conclusion, a platinum case study was undertaken and resulted in the following findings:

1. Modernised conventional operations:
    a. The potential for modernised conventional operations to improve their energy and water efficiency was shown in Fourie *et al*., (2017b). Modern drills such as electro-hydraulic, hydro-powered and hydroelectric drill were 84 to 94% more energy efficient and 24% to 66% more water efficient than pneumatic drills that are currently used in most conventional mines;
    b. These efficiencies resulted in cost savings of between R 683.40 and R 765.00 per panel per day for energy and between R 12.96 and R 37.01 per panel per day for water; and
    c. The modernisation of other mining cycle processes could potentially increase energy and water efficiencies for conventional mines.

2. Mechanised operations:
    a. The unit energy consumption for conventional operations ranged

between 0.08 and 0.59 GJ/tonne of rock broken; with an average of 0.29 GJ/tonne of rock broken for the shallow operations, 0.47 GJ/tonne of rock broken for the intermediate operations and 0.37 GJ/tonne of rock broken for all the conventional operations. The unit energy consumption for the mechanised operations ranged between 0.09 and 0.11 GJ/tonne of rock broken with an average of 0.10 GJ/tonne of rock broken. Furthermore, mechanised operations used approximately 47% less energy per tonne of rock broken compared to conventional operations with a similar depth, phase and refrigeration profile (0.19 kl/tonne of rock broken);

b. The unit electricity costs for the conventional operations ranged between R 17 and R 127 per tonne of rock broken; with an average of R 62/tonne of rock broken for the shallow operations, R 99/tonne of rock broken for intermediate operations and R 78/tonne of rock broken for all conventional operations. The unit electricity costs for the mechanised operations ranged between R 11 and R 14 per tonne of rock broken, with an average of R 13/tonne of rock broken. Furthermore, mechanised mining operations spent approximately R 27 less on electricity per tonne of rock broken compared to conventional mining operations with a similar depth, phase and refrigeration profile (R 40/tonne of rock broken);

c. The unit potable water consumption for conventional operations ranged between 0.20 and 0.64 kl/tonne of rock broken; with an average of 0.29 kl/tonne of rock broken for the shallow operations, 0.42 kl/tonne of rock broken for the intermediate operations and 0.34 kl/tonne of rock broken for all the conventional operations. The unit potable water consumption for the mechanised operations ranged between 0.02 and 0.03 kl/tonne of rock broken with an average of 0.03 kl/tonne of rock broken. Furthermore, mechanised operations used approximately 87% less potable water per tonne of rock broken compared to conventional operations with a similar depth, phase and refrigeration profile (0.24 kl/tonne of rock broken); and

d. The unit potable water costs for the conventional operations ranged between R 2.09 and R 6.51 per tonne of rock broken; with an average of R 2.93/tonne of rock broken for the shallow operations, R 4.23/tonne of rock broken for intermediate operations and R 3.49/tonne of rock broken for all conventional operations. The unit potable water costs for the mechanised operations ranged between R 0.19 and R 0.31 per tonne of rock broken, with an average of R 0.25/tonne of rock broken. Furthermore, mechanised mining operations spent approximately R 2.16 less on potable water per tonne of rock broken compared to conventional mining operations with a similar depth, phase and refrigeration profile (R 2.41/tonne of rock broken).

3. Future modern mining operations:
   a. The literature review found that the best knowledge about future mining methods for the platinum industry is that mines will be mechanised and, where possible will employ continuous mining methods. Both these methods will employ mechanised equipment and for this study, were both classified as mechanised mining methods. This study used the predicted platinum payable reserves developed by the Minerals Council of South Africa to forecast future cumulative potable water and energy consumption demand and costs from 2017 to 2043. These forecasts reiterated that the implementation of modernised mining methods, mostly mechanised mining methods, would have a significantly positive impact on the sectors energy and water consumption and consequently result in cost reductions.

The results of this study found that current modern mining operations such as modernised conventional mines or mechanised mines use less water and energy than current conventional mining methods. These consumption efficiencies resulted in significant cost savings. Furthermore, energy and water consumption and cost forecasts generated in this study show that modernisation of the platinum industry will result in increased energy and water efficiencies and consequently result in significant cost savings.

8.2 Recommendations for future research

This research was limited to the total energy and potable water requirements for underground mining activities and did not consider energy and water requirements of individual underground mining activities. In this research, it was found that detailed energy and water monitoring data posed a limitation for platinum mines in terms of distinguishing the water and energy consumption of detailed mining processes. It is thus recommended that the detailed water and energy consumption of various mining processes be investigated for platinum mines. Additionally, energy and water consumption associated with concentration and smelting were not included in this study. Smelting and concentration plants are large energy and water consumers, and it is thus recommended that this study be expanded to include smelting and concentration. It was also found that water and energy reporting vary between mining companies, making direct comparisons very difficult. Potential studies into the standardisation of water and energy reporting are also recommended.

This research was limited to potable water purchased from the municipality and did not consider the dominant water sources used for underground activities such as bulk, raw and effluent water purchased from water boards. The results in this study showed the potential for consumption and cost savings underground associated with modernisation, however, to improve the quantification of this saving it is suggested that this study be expanded to include additional water sources used underground for more accurate water accounting.

To establish the impact of water and energy associated with modernising conventional mining operations, this study found that data about modernisation trials were confidential and that limited information was available publicly. Considering that it may not be plausible for current conventional operations to modernise through employing mechanised mining systems, these mines will most likely modernise through technological and process improvements. It is thus recommended that further studies be undertaken to quantify efficiency improvements from the implementation of modernised equipment and processes at conventional mines.

Finally, it is recommended that this study be expanded to include a larger sample size. The larger sample size would increase the applicability of the study to the general populations. Additionally, because the gold sector is more advanced in monitoring detailed water and energy consumption for various mining processes, it is recommended that this study be expanded to include the gold industry.

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APPENDIX A: ETHICS WAIVER

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

Registration number: REC-101114-044

22 February 2019

Re: Mrs. Fatheela Brovko (9706025G)

To whom it may concern,

Mrs. Brovko (9706025G) is currently registered as a Masters student at the School of Mining Engineering, University of the Witwatersrand, Johannesburg. This letter is to confirm that, at the time of writing, Mrs. Brovko does not need ethical clearance for her MA study entitled '*Cost implications of modern mining methods on water and energy consumption: A South African platinum case study*'. This decision has been reached based upon a description of the project supplied by Mrs. Brovko to the University Human Research Ethics Committee (Non-Medical), which has been evaluated by the Committee Chair and two reviewers. If, however, Mrs Brovko changes the methods of data collection and analysis for this study, this decision may no longer be valid. If such changes take place, this should be communicated to the University Human Research Ethics Committee (Non-Medical) as soon as possible.

Please feel free to contact me should you require any further information.

Thank you.

Yours sincerely,
S Schoeman

Shaun Schoeman (Senior Administrative Officer)
Solomon Mahlangu House, 10th Floor, Room 10004, Jorissen Street, Braamfontein, Johannesburg
Private Bag 3, Wits 2050
T + 27(0)11 717 1408 | E Shaun.Schoeman@wits.ac.za | hrec-medical.researchoffice@wits.ac.za
www.wits.ac.za/research/about-our-research/ethics-and-research-integrity/

APPENDIX B: PERMISSION LETTERS

IMPALA
Member of the Implats Group

Head Office
GS Potgieter
Chief Operating Officer

Tel: +27 117319000
E-mail:
gerhard.potgieter@implats.co.za

13 February 2019

To whom it may concern:

PERMISSION TO USE INFORMATION

Impala Platinum received a request from Fatheela Brovko for the provision of operational water and energy consumption data for Impala Rustenburg and Two Rivers operations. She requires this data for the purpose of her MSc studies in Mineral Economics at the University of Witwatersrand. Her research project aims to identify whether the implementation of future modernised mining methods, such as mechanisation, will result in water and energy savings.

Impala Platinum hereby grant Fatheela Brovko permission to obtain the relevant information from their Impala Rustenburg and Two Rivers operations, including but not limited to:

- Water and energy consumption information;
- The mining method and equipment used;
- Production data;
- Mining depth and infrastructure; and
- Utilities cost data.

Additionally, she may undertake mine visits if required to gain a greater understanding of what type of water and energy data is collected and some complexities surrounding the collection and analysis of this data.

Impala Platinum also grants Fatheela Brovko permission to use and publish the data for her MSc studies and may mention Impala Rustenburg and Two Rivers operations as participants in the study.

Yours sincerely,

GS POTGIETER
Chief Operating Officer

Ref: xxx

NORTHAM
BOOYSENDAL

Farm Booysendal 43JT
Greater Tubatse Municipality, South Africa

Postnet Suite #199
Private Bag X20097
Lydenburg 1120
South Africa

Tel: +27 13 235 6900
Website: www.northam.co.za

To: Whom it may concern

Ref: WK/mw-700/002/409

4 February 2019

Dear Sirs,

FATHEELA BROVKO: WATER AND ENERGY USAGE RESEARCH

Northam Platinum received a request from Fatheela Brovko for the provision of operational water and energy consumption data for their Booysendal North operation. She requires this data for the purpose of her MSc studies in Mineral Economics at the University of Witwatersrand. Her research project aims to identify whether the implementation of future modernised mining methods, such as mechanisation, will result in water and energy savings.

Booysendal hereby grants Fatheela Brovko permission to obtain the relevant information from its Booysendal North operation, including but not limited to:

- Water and energy consumption information;
- The mining method and equipment used;
- Production data;
- Mining depth and infrastructure; and
- Utilities cost data.

Additionally, she may undertake mine visits if required to gain a greater understanding of what type of water and energy data is collected and some complexities surrounding the collection and analysis of this data.

Booysendal also grants Fatheela Brovko permission to use and publish the data for her MSc studies and may mention Booysendal mine as a participant in the study.

W.v.

Kind regards

05/02/2019

WONDERBOY KEKANA
GENERAL MANAGER
BOOYSENDAL PLATINUM (PTY) LTD

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APPENDIX C: ANNUAL DATA FOR EACH OPERATION

Table C1 Annual data for Operation 1 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	-	44.60	74.48	92.43	123.29
Electric Energy (GJ)	-	160 549.95	268 134.08	332 741.70	443 842.16
Tonnes of rock broken	125 953.00	160 887.00	496 042.95	752 128.00	1 143 551.00
Water (m^3)	-	192 165.00	274 460.00	341 810.00	407 515.00
Unit water (kl/t)	-	1.19	0.55	0.45	0.36
Unit energy (GJ)/t	-	1.00	0.54	0.44	0.39

Table C2 Annual data for Operation 2 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	203.08	171.06	187.22	199.89	215.65
Electric Energy (GJ)	731 105.29	615 831.56	673 986.39	719 601.12	776 357.61
Diesel (l)	62 642.00	74 295.00	66 900.00	81 588.00	74 002.00
Diesel (GJ)	2 379.77	2 822.47	2 541.53	3 099.53	2 811.34
Total Energy (GJ)	733 485.06	618 654.03	676 527.92	722 700.65	779 168.95
Tonnes of rock broken	1 776 515.00	1 038 304.06	1 375 275.00	1 874 334.00	1 975 614.00
Water (m^3)	590 595.00	439 421.00	630 726.00	597 961.00	731 808.40
Unit water (kl/t)	0.33	0.42	0.46	0.32	0.37
Unit Electric Energy (GJ)/t	0.41	0.59	0.49	0.38	0.39
Unit Diesel Energy (GJ) /t	0.001	0.003	0.002	0.002	0.001
Unit energy (GJ)/t	0.41	0.60	0.49	0.39	0.39

Table C3 Annual data for Operation 3 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	103.51	92.78	118.90	132.91	155.08
Electric Energy (GJ)	372624.16	334025.77	428026.94	478474.82	558294.97
Tonnes of rock broken	1106405.00	587208.00	1007439.00	1341726.00	1429488.00
Water (m^3)	241787.00	243680.96	470875.00	365438.00	388852.20
Unit water (kl/t)	0.22	0.41	0.47	0.27	0.27
Unit energy (GJ)/t	0.34	0.57	0.42	0.36	0.39

Table C4 Annual data for Operation 4 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	65.95	51.32	62.70	63.94	64.37
Electric Energy (GJ)	237 431.64	184 740.33	225 718.03	230 186.86	231 721.72
Tonnes of rock broken	636 631.00	433 822.00	586 796.00	657 976.00	533 246.00
Water (m^3)	172 768.00	145 201.68	191 848.00	184 390.00	160 103.60
Unit water (kl/t)	0.27	0.33	0.33	0.28	0.30
Unit energy (GJ)/t	0.37	0.43	0.38	0.35	0.43

Table C5 Annual data for Operation 5 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	221.72	147.54	182.88	166.69	188.84
Electric Energy (GJ)	798 189.34	531 137.79	658 385.48	600 089.49	679 841.55
Diesel (l)	538 004.00	272 508.00	591 538.00	402 361.00	380 523.00
Diesel (GJ)	20 438.77	10 352.58	22 472.53	15 285.69	14 456.07
Total Energy (GJ)	818 628.11	541 490.37	680 858.01	615 375.18	694 297.62
Tonnes of rock broken	1 499 982.00	885 044.00	1 430 386.00	1 124 950.00	1 175 055.00
Water (m^3)	516 646.00	354 108.10	604 341.00	563 539.00	614 430.90
Unit water (kl/t)	0.34	0.40	0.42	0.50	0.52
Unit Electric Energy (GJ)/t	0.53	0.60	0.46	0.53	0.58
Unit Diesel Energy (GJ) /t	0.01	0.01	0.02	0.01	0.01
Unit energy (GJ)/t	0.55	0.61	0.48	0.55	0.59

Table C6 Annual data for Operation 6 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	71.22	62.77	85.21	108.07	128.97
Electric Energy (GJ)	256 388.96	225 972.58	306 763.12	389 041.03	464 288.65
Diesel (l)	720 040.00	487 746.00	593 152.00	484 749.00	440 051.00
Diesel (GJ)	27 354.32	18 529.47	22 533.84	18 415.61	16 717.54
Total Energy (GJ)	283 743.27	244 502.05	329 296.97	407 456.64	481 006.19
Tonnes of rock broken	773 966.00	473 432.00	770 948.00	1 014 575.00	1 187 719.00
Water (m^3)	290 896.00	270 241.51	336 068.00	351 606.00	380 571.10
Unit water (kl/t)	0.38	0.57	0.44	0.35	0.32
Unit Electric Energy (GJ)/t	0.33	0.48	0.40	0.38	0.39
Unit Diesel Energy (GJ) /t	0.04	0.04	0.03	0.02	0.01
Unit energy (GJ)/t	0.37	0.52	0.43	0.40	0.40

Table C7 Annual data for Operation 7 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	160.35	132.18	139.67	126.61	109.76
Electric Energy (GJ)	577263.19	475841.65	502828.15	455810.16	395140.99
Diesel (l)	809831.00	479899.00	665801.00	333890.28	8001.00
Diesel (GJ)	30765.48	18231.36	25293.78	12684.49	303.96
Total Energy (GJ)	608028.67	494073.01	528121.93	468494.65	395444.95
Tonnes of rock broken	1456085.00	820682.54	1093774.00	1079963.00	943568.00
Water (m^3)	350455.00	307982.05	278178.00	302889.00	359885.80
Unit water (kl/t)	0.24	0.38	0.25	0.28	0.38
Unit Electric Energy (GJ)/t	0.40	0.58	0.46	0.42	0.42
Unit Diesel Energy (GJ) /t	0.02	0.02	0.02	0.01	0.00
Unit energy (GJ)/t	0.42	0.60	0.48	0.43	0.42

Table C8 Annual data for Operation 8 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	177.90	130.38	162.56	179.43	193.91
Electric Energy (GJ)	640 431.26	469 358.91	585 217.33	645 961.89	698 059.44
Tonnes of rock broken	1 679 646.00	998 596.00	1 311 475.00	1 335 766.00	1 193 015.00
Water (m^3)	551 199.00	509 790.06	573 465.00	518 867.00	550 949.20
Unit water (kl/t)	0.33	0.51	0.44	0.39	0.46
Unit energy (GJ)/t	0.38	0.47	0.45	0.48	0.59

Table C9 Annual data for Operation 9 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	31.73	17.25	25.98	25.81	22.43
Electric Energy (GJ)	114 210.86	62 116.61	93 525.21	92 898.77	80 734.52
Tonnes of rock broken	673 673.00	293 896.00	376 426.00	334 770.00	234 276.00
Water (m^3)	158 068.00	86 685.11	108 752.00	99 856.00	110 776.90
Unit water (kl/t)	0.23	0.29	0.29	0.30	0.47
Unit energy (GJ)/t	0.17	0.21	0.25	0.28	0.34

Table C10 Annual data for Operation 10 for 2013 to 2016

	2013	2014	2015	2016
Electricity (GWh)	33.11	21.63	23.84	16.48
Electric Energy (GJ)	119 192.40	77 853.47	85 828.00	59 328.15
Tonnes of rock broken	424 348.00	185 282.00	213 413.00	131 944.00
Water (m^3)	75 593.00	42 523.35	72 406.00	57 278.00
Unit water (kl/t)	0.18	0.23	0.34	0.43
Unit energy (GJ)/t	0.28	0.42	0.40	0.45

Table C11 Annual data for Operation 11 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	51.38	33.40	38.17	39.62	40.60
Electric Energy (GJ)	184 971.08	120 257.70	137 409.18	142 624.66	146 158.73
Tonnes of rock broken	599 368.00	323 096.00	438 860.00	526 761.00	482 446.00
Water (m^3)	110 616.00	77 441.91	121 724.00	114 708.00	119 776.90
Unit water (kl/t)	0.18	0.24	0.28	0.22	0.25
Unit energy (GJ)/t	0.31	0.37	0.31	0.27	0.30

Table C12 Annual data for Operation 12 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	20.21	16.46	20.81	18.08	14.63
Electric Energy (GJ)	72 742.81	59 251.40	74 933.19	65 099.83	52 670.61
Tonnes of rock broken	469 218.00	259 478.00	356 038.00	357 538.00	186 236.00
Water (m^3)	99 110.00	76 767.22	102 550.00	78 608.00	62 373.30
Unit water (kl/t)	0.21	0.30	0.29	0.22	0.33
Unit energy (GJ)/t	0.16	0.23	0.21	0.18	0.28

Table C13 Annual data for Operation 13 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	22.94	14.14	17.40	19.15	22.57
Electric Energy (GJ)	82 590.99	50 919.11	62 640.75	68 935.82	81 243.10
Tonnes of rock broken	471 071.00	259 498.00	404 572.00	508 631.00	591 437.00
Water (m^3)	55 453.00	63 936.70	87 474.00	88 890.00	149 398.90
Unit water (kl/t)	0.12	0.25	0.22	0.17	0.25
Unit energy (GJ)/t	0.18	0.20	0.15	0.14	0.14

Table C14 Annual data for Operation 14 for 2013 to 2017

	2013	2014	2015	2016	2017
Electricity (GWh)	6.08	5.04	5.89	7.94	7.89
Electric Energy (GJ)	21898.57	18153.27	21186.84	28573.79	28386.45
Tonnes of rock broken	333664.00	202872.00	270771.00	338880.00	334394.00
Water (m^3)	196779.00	58770.00	43740.00	39370.00	45722.00
Unit water (kl/t)	0.59	0.29	0.16	0.12	0.14
Unit energy (GJ)/t	0.07	0.09	0.08	0.08	0.08

Table C15 Annual data for Operation 15 for 2013 to 2017

	2013 (6 months)	2014	2015	2016	2017
Electricity (GWh)	34.05	36.49	37.73	38.44	38.77
Electric Energy (GJ)	114 415.61	122 601.96	126 775.80	129 168.16	130 256.33
Diesel (l)	2 181 641.00	2 224 339.00	2 197 416.00	2 244 166.00	2 359 479.00
Diesel (GJ)	82 880.54	84 502.64	83 479.83	85 255.87	89 636.61
Total Energy (GJ)	197 296.15	207 104.60	210 255.63	214 424.03	219 892.94
Tonnes of rock broken	1 268 510.00	2 451 422.00	2 319 422.00	2 204 010.00	2 314 284.70
Water (m^3)	33 959.00	67 029.00	66 724.00	87 291.00	69 238.00
Unit water (kl/t)	0.03	0.03	0.03	0.04	0.03
Unit Electric Energy (GJ)/t	0.05	0.05	0.05	0.06	0.06
Unit Diesel Energy (GJ) /t	0.03	0.03	0.04	0.04	0.04
Unit energy (GJ)/t	0.08	0.08	0.09	0.10	0.10

Table C16 Annual data for Operation 16 for 2013 to 2017

	2013 (6 months)	2014	2015	2016	2017
Electricity (GWh)	15.13	16.22	16.77	17.09	17.23
Electric Energy (GJ)	50 851.38	54 489.76	56 344.80	57 408.07	57 891.70
Diesel (l)	1 438 218.00	1 761 966.00	1 817 476.00	1 896 796.00	1 923 318.00
Diesel (GJ)	54 637.90	66 937.09	69 045.91	72 059.28	73 066.85
Total Energy (GJ)	105 489.28	121 426.85	125 390.71	129 467.35	130 958.55
Tonnes of rock broken	584 858.00	1 272 360.00	1 383 245.00	1 499 154.00	1 474 638.60
Water (m^3)	11 091.00	24 784.00	44 623.00	33 390.00	44 155.00
Unit water (kl/t)	0.02	0.02	0.03	0.02	0.03
Unit Electric Energy (GJ)/t	0.04	0.04	0.04	0.04	0.04
Unit Diesel Energy (GJ) /t	0.05	0.05	0.05	0.05	0.05
Unit energy (GJ)/t	0.09	0.10	0.09	0.09	0.09

Table C17 Annual data for Operation 17 for 2013 to 2016

	2013	2014	2015	2016
Electricity (GWh)	18.45	36.52	44.05	42.71
Electric Energy (GJ)	66 418.25	131 479.52	158 584.69	153 752.78
Diesel (l)	1 691 211.00	1 870 445.00	2 167 886.00	2 544 938.00
Diesel (GJ)	64 249.11	71 058.21	82 357.99	96 682.19
Total Energy (GJ)	130 667.36	202 537.73	240 942.68	250 434.98
Tonnes of rock broken	1 233 088.00	1 674 629.00	2 137 517.00	2 607 520.00
Water (m^3)	-	74 145.51	24 510.29	11 087.28
Unit water (kl/t)	-	0.04	0.01	0.00425
Unit Electric Energy (GJ)/t	0.05	0.08	0.07	0.06
Unit Diesel Energy (GJ) /t	0.05	0.04	0.04	0.04
Unit energy (GJ)/t	0.11	0.12	0.11	0.10

APPENDIX D: DATA ANALYSIS RESULTS

Table D1 Annual unit energy consumption (GJ/tonne of rock broken) between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Annual unit energy consumption (GJ/tonne of rock broken) for:				
				2013	2014	2015	2016	2017
Operation 1	Conventional	Intermediate	4	-	1.00	0.54	0.44	0.39
Operation 2	Conventional	Intermediate	5	0.41	0.60	0.49	0.39	0.39
Operation 3	Conventional	Intermediate	5	0.34	0.57	0.42	0.36	0.39
Operation 4	Conventional	Intermediate	5	0.37	0.43	0.38	0.35	0.43
Operation 5	Conventional	Intermediate	5	0.55	0.61	0.48	0.55	0.59
Operation 6	Conventional	Intermediate	5	0.37	0.52	0.43	0.40	0.40
Operation 7	Conventional	Shallow	5	0.42	0.60	0.48	0.43	0.42
Operation 8	Conventional	Shallow	5	0.38	0.47	0.45	0.48	0.59
Operation 9	Conventional	Shallow	5	0.17	0.21	0.25	0.28	0.34
Operation 10	Conventional	Shallow	4	0.28	0.42	0.40	0.45	-
Operation 11	Conventional	Shallow	5	0.31	0.37	0.31	0.27	0.30
Operation 12	Conventional	Shallow	5	0.16	0.23	0.21	0.18	0.28
Operation 13	Conventional	Shallow	5	0.18	0.20	0.15	0.14	0.14
Operation 14	Conventional	Shallow	5	0.07	0.09	0.08	0.08	0.08
Operation 15	Mechanised	Shallow	5	0.08	0.08	0.09	0.10	0.10
Operation 16	Mechanised	Shallow	5	0.09	0.10	0.09	0.09	0.09
Operation 17	Mechanised	Shallow	4	0.11	0.12	0.11	0.10	-

Table D2 Average unit energy consumption (GJ/tonne rock broken) and average production in tonnes (of rock broken) between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Average unit energy consumption (GJ/tonne of rock broken)	Average production in tonnes (of rock broken)
Operation 1	Conventional	Intermediate	4	0.59	638 152
Operation 2	Conventional	Intermediate	5	0.46	1 608 008
Operation 3	Conventional	Intermediate	5	0.42	1 094 453
Operation 4	Conventional	Intermediate	5	0.39	569 694
Operation 5	Conventional	Intermediate	5	0.55	1 223 083
Operation 6	Conventional	Intermediate	5	0.42	844 128
Operation 7	Conventional	Shallow	5	0.47	1 078 815
Operation 8	Conventional	Shallow	5	0.47	1 303 700
Operation 9	Conventional	Shallow	5	0.25	382 608
Operation 10	Conventional	Shallow	4	0.39	238 747
Operation 11	Conventional	Shallow	5	0.31	474 106
Operation 12	Conventional	Shallow	5	0.21	325 702
Operation 13	Conventional	Shallow	5	0.16	447 042
Operation 14	Conventional	Shallow	5	0.08	296 116
Operation 15	Mechanised	Shallow	5	0.09	2 111 530
Operation 16	Mechanised	Shallow	5	0.09	1 242 851
Operation 17	Mechanised	Shallow	4	0.11	1 913 189

Table D3 Average unit energy consumption (GJ/tonne of rock broken), depth (m) and average production in tonnes (of rock broken) between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Average unit energy consumption (GJ/tonne of rock broken)	Depth (m)	Average production in tonnes (of rock broken)
Operation 1	Conventional	Intermediate	4	0.59	1650	638 152
Operation 2	Conventional	Intermediate	5	0.46	1251	1 608 008
Operation 3	Conventional	Intermediate	5	0.42	1180	1 094 453
Operation 4	Conventional	Intermediate	5	0.39	1126	569 694
Operation 5	Conventional	Intermediate	5	0.55	1157	1 223 083
Operation 6	Conventional	Intermediate	5	0.42	1063	844 128
Operation 7	Conventional	Shallow	5	0.47	961	1 078 815
Operation 8	Conventional	Shallow	5	0.47	766	1 303 700
Operation 9	Conventional	Shallow	5	0.25	688	382 608
Operation 10	Conventional	Shallow	4	0.39	668	238 747
Operation 11	Conventional	Shallow	5	0.31	496	474 106
Operation 12	Conventional	Shallow	5	0.21	337	325 702
Operation 13	Conventional	Shallow	5	0.16	257	447 042
Operation 14	Conventional	Shallow	5	0.08	195	296 116
Operation 15	Mechanised	Shallow	5	0.09	450	2 111 530
Operation 16	Mechanised	Shallow	5	0.09	450	1 242 851
Operation 17	Mechanised	Shallow	4	0.11	450	1 913 189

Table D4 Annual unit electricity costs (R/tonne of rock broken) between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Annual unit electricity costs (R/tonne of rock broken) for:				
				2013	2014	2015	2016	2017
Operation 1	Conventional	Intermediate	4	-	192.71	117.13	104.21	93.70
Operation 2	Conventional	Intermediate	5	73.92	114.54	106.20	90.44	94.87
Operation 3	Conventional	Intermediate	5	60.49	109.85	92.07	84.00	94.29
Operation 4	Conventional	Intermediate	5	66.99	82.24	83.35	82.41	104.91
Operation 5	Conventional	Intermediate	5	95.58	115.89	99.74	125.65	139.67
Operation 6	Conventional	Intermediate	5	59.50	92.17	86.22	90.32	94.37
Operation 7	Conventional	Shallow	5	71.21	111.97	99.62	99.42	101.10
Operation 8	Conventional	Shallow	5	68.48	90.77	96.70	113.91	141.26
Operation 9	Conventional	Shallow	5	30.45	40.82	53.84	65.37	83.20
Operation 10	Conventional	Shallow	4	50.45	81.14	87.15	105.92	-
Operation 11	Conventional	Shallow	5	55.43	71.88	67.85	63.78	73.14
Operation 12	Conventional	Shallow	5	27.85	44.10	45.61	42.89	68.28
Operation 13	Conventional	Shallow	5	31.49	37.89	33.55	31.93	33.16
Operation 14	Conventional	Shallow	5	11.79	17.28	16.96	19.86	20.49
Operation 15	Mechanised	Shallow	5	17.36	10.35	12.69	14.79	14.56
Operation 16	Mechanised	Shallow	5	16.73	8.86	9.46	9.66	10.15
Operation 17	Mechanised	Shallow	4	9.67	15.16	16.08	13.89	-

Table D5 Average unit electricity costs (R/tonne of rock broken) and average production in tonnes (of broken rock) between 2013 and 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Average unit electricity costs (R/tonne of rock broken)	Average production in tonnes (of rock broken)
Operation 1	Conventional	Intermediate	4	126.94	638 152
Operation 2	Conventional	Intermediate	5	95.99	1 608 008
Operation 3	Conventional	Intermediate	5	88.14	1 094 453
Operation 4	Conventional	Intermediate	5	83.98	569 694
Operation 5	Conventional	Intermediate	5	115.31	1 223 083
Operation 6	Conventional	Intermediate	5	84.52	844 128
Operation 7	Conventional	Shallow	5	96.66	1 078 815
Operation 8	Conventional	Shallow	5	102.22	1 303 700
Operation 9	Conventional	Shallow	5	54.73	382 608
Operation 10	Conventional	Shallow	4	81.16	238 747
Operation 11	Conventional	Shallow	5	66.41	474 106
Operation 12	Conventional	Shallow	5	45.74	325 702
Operation 13	Conventional	Shallow	5	33.60	447 042
Operation 14	Conventional	Shallow	5	17.28	296 116
Operation 15	Mechanised	Shallow	5	13.95	2 111 530
Operation 16	Mechanised	Shallow	5	10.97	1 242 851
Operation 17	Mechanised	Shallow	4	13.70	1 913 189

Table D6 Annual unit potable water consumption (kl/tonne of rock broken) between 2013 to 2017

Operation	**Type of Mine**	**Depth Classification**	**Number of years over which the data was averaged**	**Annual unit potable water consumption (kl/tonne of rock broken) for:**				
				2013	**2014**	**2015**	**2016**	**2017**
Operation 1	Conventional	Intermediate	4	-	1.19	0.55	0.45	0.36
Operation 2	Conventional	Intermediate	5	0.33	0.42	0.46	0.32	0.37
Operation 3	Conventional	Intermediate	5	0.22	0.41	0.47	0.27	0.27
Operation 4	Conventional	Intermediate	5	0.27	0.33	0.33	0.28	0.30
Operation 5	Conventional	Intermediate	5	0.34	0.40	0.42	0.50	0.52
Operation 6	Conventional	Intermediate	5	0.38	0.57	0.44	0.35	0.32
Operation 7	Conventional	Shallow	5	0.24	0.38	0.25	0.28	0.38
Operation 8	Conventional	Shallow	5	0.33	0.51	0.44	0.39	0.46
Operation 9	Conventional	Shallow	5	0.23	0.29	0.29	0.30	0.47
Operation 10	Conventional	Shallow	4	0.18	0.23	0.34	0.43	-
Operation 11	Conventional	Shallow	5	0.18	0.24	0.28	0.22	0.25
Operation 12	Conventional	Shallow	5	0.21	0.30	0.29	0.22	0.33
Operation 13	Conventional	Shallow	5	0.12	0.25	0.22	0.17	0.25
Operation 14	Conventional	Shallow	5	0.59	0.29	0.16	0.12	0.14
Operation 15	Mechanised	Shallow	5	0.03	0.03	0.03	0.04	0.03
Operation 16	Mechanised	Shallow	5	0.02	0.02	0.03	0.02	0.03
Operation 17	Mechanised	Shallow	3	-	0.04	0.01	0.0043	-

Table D7 Average unit potable water consumption (kl/tonne of rock broken) and average production in tonnes (of rock broken) between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Average unit potable water consumption (kl/tonne of rock broken)	Average production in tonnes (of rock broken)
Operation 1	Conventional	Intermediate	4	0.64	638 152
Operation 2	Conventional	Intermediate	5	0.38	1 608 008
Operation 3	Conventional	Intermediate	5	0.33	1 094 453
Operation 4	Conventional	Intermediate	5	0.30	569 694
Operation 5	Conventional	Intermediate	5	0.44	1 223 083
Operation 6	Conventional	Intermediate	5	0.41	844 128
Operation 7	Conventional	Shallow	5	0.31	1 078 815
Operation 8	Conventional	Shallow	5	0.43	1 303 700
Operation 9	Conventional	Shallow	5	0.32	382 608
Operation 10	Conventional	Shallow	4	0.30	238 747
Operation 11	Conventional	Shallow	5	0.23	474 106
Operation 12	Conventional	Shallow	5	0.27	325 702
Operation 13	Conventional	Shallow	5	0.20	447 042
Operation 14	Conventional	Shallow	5	0.26	296 116
Operation 15	Mechanised	Shallow	5	0.03	2 111 530
Operation 16	Mechanised	Shallow	5	0.02	1 242 851
Operation 17	Mechanised	Shallow	3	0.02	2 139 889

Table D8 Average unit potable water consumption (kl/tonne of rock broken), depth (m) and average production in tonnes (of rock broken) between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Average unit potable water consumption (kl/tonne of rock broken)	Depth (m)	Average production in tonnes (of rock broken)
Operation 1	Conventional	Intermediate	4	0.64	1650	638 152
Operation 2	Conventional	Intermediate	5	0.38	1251	1 608 008
Operation 3	Conventional	Intermediate	5	0.33	1180	1 094 453
Operation 4	Conventional	Intermediate	5	0.30	1126	569 694
Operation 5	Conventional	Intermediate	5	0.44	1157	1 223 083
Operation 6	Conventional	Intermediate	5	0.41	1063	844 128
Operation 7	Conventional	Shallow	5	0.31	961	1 078 815
Operation 8	Conventional	Shallow	5	0.43	766	1 303 700
Operation 9	Conventional	Shallow	5	0.32	688	382 608
Operation 10	Conventional	Shallow	4	0.30	668	238 747
Operation 11	Conventional	Shallow	5	0.23	496	474 106
Operation 12	Conventional	Shallow	5	0.27	337	325 702
Operation 13	Conventional	Shallow	5	0.20	257	447 042
Operation 14	Conventional	Shallow	5	0.26	195	296 116
Operation 15	Mechanised	Shallow	5	0.03	450	2 111 530
Operation 16	Mechanised	Shallow	5	0.02	450	1 242 851
Operation 17	Mechanised	Shallow	3	0.02	450	2 139 889

Table D9 Annual unit potable water cost (R/tonne of rock broken) for the 17 mining operations between 2013 to 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Annual unit potable water cost (R/tonne rock broken) for:				
				2013	2014	2015	2016	2017
Operation 1	Conventional	Intermediate	4		10.73	5.64	5.18	4.48
Operation 2	Conventional	Intermediate	5	2.52	3.80	4.67	3.64	4.65
Operation 3	Conventional	Intermediate	5	1.65	3.73	4.76	3.10	3.42
Operation 4	Conventional	Intermediate	5	2.05	3.01	3.33	3.19	3.77
Operation 5	Conventional	Intermediate	5	2.61	3.59	4.31	5.71	6.57
Operation 6	Conventional	Intermediate	5	2.85	5.13	4.44	3.95	4.02
Operation 7	Conventional	Shallow	5	1.82	3.37	2.59	3.20	4.79
Operation 8	Conventional	Shallow	5	2.48	4.58	4.46	4.43	5.80
Operation 9	Conventional	Shallow	5	1.78	2.65	2.94	3.40	5.94
Operation 10	Conventional	Shallow	4	1.35	2.06	3.46	4.95	
Operation 11	Conventional	Shallow	5	1.40	2.15	2.83	2.48	3.12
Operation 12	Conventional	Shallow	5	1.60	2.66	2.94	2.51	4.21
Operation 13	Conventional	Shallow	5	0.89	2.21	2.20	1.99	3.17
Operation 14	Conventional	Shallow	5	4.46	2.60	1.65	1.32	1.72
Operation 15	Mechanised	Shallow	5	0.20	0.25	0.29	0.45	0.38
Operation 16	Mechanised	Shallow	5	0.14	0.17	0.33	0.25	0.38
Operation 17	Mechanised	Shallow	4		0.40	0.12	0.0485	

Table D10 Average unit potable water cost (R/tonne rock broken) and average production in tonnes (of broken rock) between 2013 and 2017

Operation	Type of Mine	Depth Classification	Number of years over which the data was averaged	Average unit potable water cost (R/tonne rock broken)	Average production in tonnes (of rock broken)
Operation 1	Conventional	Intermediate	4	6.51	638 152
Operation 2	Conventional	Intermediate	5	3.86	1 608 008
Operation 3	Conventional	Intermediate	5	3.33	1 094 453
Operation 4	Conventional	Intermediate	5	3.07	569 694
Operation 5	Conventional	Intermediate	5	4.56	1 223 083
Operation 6	Conventional	Intermediate	5	4.08	844 128
Operation 7	Conventional	Shallow	5	3.15	1 078 815
Operation 8	Conventional	Shallow	5	4.35	1 303 700
Operation 9	Conventional	Shallow	5	3.34	382 608
Operation 10	Conventional	Shallow	4	2.95	238 747
Operation 11	Conventional	Shallow	5	2.40	474 106
Operation 12	Conventional	Shallow	5	2.78	325 702
Operation 13	Conventional	Shallow	5	2.09	447 042
Operation 14	Conventional	Shallow	5	2.35	296 116
Operation 15	Mechanised	Shallow	5	0.31	2 111 530
Operation 16	Mechanised	Shallow	5	0.26	1 242 851
Operation 17	Mechanised	Shallow	4	0.19	1 913 189

Table D11 Production projections of the South African platinum mines for conventional mining and mechanised mining (including 24-7 mechanised mining) from the 2017 to 2043 (adapted from Fourie *et al*. (2017a) and Rupprecht (2017))

Year	Conventional mining forecasted production in tonnes	Mechanised and 24-7 mechanised mining forecasted production in tonnes
2017	33688278	3326416
2018	32778732	4230237
2019	32503459	4046563
2020	27099614	4406517
2021	26731788	4313964
2022	25823434	4944659
2023	25905968	3955441
2024	13487429	11780449
2025	7002529	15918134
2026	2409713	19242403
2027	2312390	19873336
2028	2034254	23740757
2029	1845570	24909117
2030	0	27826678
2031	-	27817852
2032	-	27809503
2033	-	27800916
2034	-	27793998
2035	-	28685416
2036	-	19684175
2037	-	19764086
2038	-	19578741
2039	-	19569916
2040	-	19560135
2041	-	19553934
2042	-	19005534
2043	-	0

Table D12 Energy demand forecasts for conventional mines (GJ), mechanised mines (GJ) and the platinum sector (GJ); and cumulative production forecast (million tonnes) from 2017 to 2043

Year	Energy demand forecast (GJ) for conventional mines	Energy demand forecast (GJ) mechanised mining	Energy demand forecast (GJ) for the platinum sector (GJ)	Cumulative production forecast (million tonnes)
2017	12464663	332642	12797305	37.0
2018	12128131	423024	12551155	37.0
2019	12026280	404656	12430936	36.6
2020	10026857	440652	10467509	31.5
2021	9890761	431396	10322158	31.0
2022	9554671	494466	10049136	30.8
2023	9585208	395544	9980752	29.9
2024	4990349	1178045	6168394	25.3
2025	2590936	1591813	4182749	22.9
2026	891594	1924240	2815834	21.7
2027	855584	1987334	2842918	22.2
2028	752674	2374076	3126750	25.8
2029	682861	2490912	3173773	26.8
2030	0	2782668	2782668	27.8
2031	-	2781785	2781785	27.8
2032	-	2780950	2780950	27.8
2033	-	2780092	2780092	27.8
2034	-	2779400	2779400	27.8
2035	-	2868542	2868542	28.7
2036	-	1968418	1968418	19.7
2037	-	1976409	1976409	19.8
2038	-	1957874	1957874	19.6
2039	-	1956992	1956992	19.6
2040	-	1956014	1956014	19.6
2041	-	1955393	1955393	19.6
2042	-	1900553	1900553	19.0
2043	-	0	0	0.0

Table D13 Electricity demand forecasts for conventional mines (GWh) and mechanised mines (GWh), the worst-case electricity tariff forecast (2017 Rc/kWh) and cumulative electricity cost forecast for the platinum sector (R million) from 2017 to 2043

Year	Conventional mining electricity demand forecast (GWh)	Mechanised mining electricity demand forecast (GWh)	Worst-case electricity tariff forecast (2017 Rc/kWh)	Cumulative electricity cost forecast for the platinum sector (R million)
2017	3427.78	50.82	83	2871.6
2018	3335.24	64.63	103	3490.6
2019	3307.23	61.82	111	3756.2
2020	2757.39	67.32	113	3198.4
2021	2719.96	65.91	116	3220.2
2022	2627.53	75.54	114	3094.2
2023	2635.93	60.43	113	3039.6
2024	1372.35	179.98	112	1732.5
2025	712.51	243.19	110	1054.8
2026	245.19	293.98	111	598.4
2027	235.29	303.62	111	600.8
2028	206.99	362.71	111	635.1
2029	187.79	380.56	114	647.1
2030	0.00	425.13	119	506.7
2031	-	424.99	121	513.4
2032	-	424.87	122	517.0
2033	-	424.74	125	531.0
2034	-	424.63	128	543.6
2035	-	438.25	129	566.4
2036	-	300.73	131	393.9
2037	-	301.95	131	395.2
2038	-	299.12	136	405.9
2039	-	298.98	136	407.2
2040	-	298.84	140	417.1
2041	-	298.74	144	429.6
2042	-	290.36	148	429.0
2043	-	0.00	148	0.0

Table D14 Potable water demand forecasts for conventional mines (GL), mechanised mines (GL) and the platinum sector (GL); and cumulative production forecast (million tonnes) from 2017 to 2043

Year	Conventional mining potable water demand forcast (GL)	Mechanised mining potable water demand forecast (GL)	Cumulative platinum industry potable water demand (GL)	Cumulative production forecast (million tonnes)
2017	11.45	0.10	11.55	37.0
2018	11.14	0.13	11.27	37.0
2019	11.05	0.12	11.17	36.6
2020	9.21	0.13	9.35	31.5
2021	9.09	0.13	9.22	31.0
2022	8.78	0.15	8.93	30.8
2023	8.81	0.12	8.93	29.9
2024	4.59	0.35	4.94	25.3
2025	2.38	0.48	2.86	22.9
2026	0.82	0.58	1.40	21.7
2027	0.79	0.60	1.38	22.2
2028	0.69	0.71	1.40	25.8
2029	0.63	0.75	1.37	26.8
2030	0.00	0.83	0.83	27.8
2031		0.83	0.83	27.8
2032		0.83	0.83	27.8
2033		0.83	0.83	27.8
2034		0.83	0.83	27.8
2035		0.86	0.86	28.7
2036		0.59	0.59	19.7
2037		0.59	0.59	19.8
2038		0.59	0.59	19.6
2039		0.59	0.59	19.6
2040		0.59	0.59	19.6
2041		0.59	0.59	19.6
2042		0.57	0.57	19.0
2043		0.00	0.00	0.0

Table D15 Linearly extrapolated Rand Water tariffs (R/ kl) from 2007 to 2043

Year	Linearly extrapolated potable water forecasted tariffs (R/kl)	Lower confidence bound (R/kl)	Upper confidence bound (R/kl)
2007	4.36		
2008	4.56	-	-
2009	4.84	-	-
2010	5.25	-	-
2011	5.99	-	-
2012	6.76	-	-
2013	7.57	-	-
2014	8.98	-	-
2015	10.19	-	-
2016	11.4	-	-
2017	12.56	12.56	12.56
2018	13.75	13.12	14.38
2019	14.92	13.78	16.05
2020	16.08	14.27	17.90
2021	17.25	14.63	19.86
2022	18.41	14.89	21.93
2023	19.58	15.06	24.09
2024	20.74	15.14	26.34
2025	21.90	15.15	28.65
2026	23.07	15.10	31.04
2027	24.23	14.97	33.49
2028	25.40	14.78	36.01
2029	26.56	14.53	38.59
2030	27.72	14.22	41.23
2031	28.89	13.86	43.92
2032	30.05	13.44	46.66
2033	31.22	12.97	49.46
2034	32.38	12.45	52.31
2035	33.55	11.89	55.20
2036	34.71	11.27	58.15
2037	35.87	10.61	61.14
2038	37.04	9.90	64.17
2039	38.20	9.15	67.25
2040	39.37	8.36	70.38
2041	40.53	7.52	73.54
2042	41.69	6.64	76.75
2043	42.86	5.72	79.99

Table D16 Average potable water demand forecast for conventional mines (GL), mechanised mines (GL), the linearly extrapolated water tariffs (cents/ kWh) and the forecasted potable water costs for the platinum sector (R million) from 2017 to 2043

Year	Conventional mining potable water demand forecast (GL)	Mechanised mining potable water demand forecast (GL)	Linearly extrapolated potable water tariff (R/kl)	Cumulative potable water cost forecast for the platinum sector (R million)
2017	11.45	0.10	12.56	145.12
2018	11.14	0.13	13.75	155.03
2019	11.05	0.12	14.92	166.68
2020	9.21	0.13	16.08	150.31
2021	9.09	0.13	17.25	158.98
2022	8.78	0.15	18.41	164.38
2023	8.81	0.12	19.58	174.74
2024	4.59	0.35	20.74	102.43
2025	2.38	0.48	21.90	62.61
2026	0.82	0.58	23.07	32.22
2027	0.79	0.60	24.23	33.50
2028	0.69	0.71	25.40	35.65
2029	0.63	0.75	26.56	36.51
2030	0.00	0.83	27.72	23.14
2031	-	0.83	28.89	24.11
2032	-	0.83	30.05	25.07
2033	-	0.83	31.22	26.04
2034	-	0.83	32.38	27.00
2035	-	0.86	33.55	28.87
2036	-	0.59	34.71	20.50
2037	-	0.59	35.87	21.27
2038	-	0.59	37.04	21.75
2039	-	0.59	38.20	22.43
2040	-	0.59	39.37	23.10
2041	-	0.59	40.53	23.78
2042	-	0.57	41.69	23.77
2043	-	0.00	42.86	0.00