A Mining Feasibility Case Study Analysis of Fuel Cell Technology Application to Stimulate Platinum Beneficiation in South Africa

Disebo Motsheoa Letanta

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University of the Witwatersrand, Johannesburg, in partial fulfilment of the
requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in Mining Engineering at 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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ABSTRACT

This study entailed determining the feasibility of using a stationary fuel cell to power two different mining operations. These were a deep level gold mine (Mponeng Gold Mine and its plant) and a surface processing operation (Mine Waste Solutions), both belonging to AngloGold Ashanti. The premise of this study was that limited local adoption of fuel cells could possibly act to prompt their local manufacturing and result in increased platinum beneficiation to contribute towards the much needed economic growth and development for South Africa.

For this feasibility analysis, the Molten Carbonate Fuel Cell was used. The study revealed that the use of a large, stationary fuel cell to power the selected operations was not feasible due to high capital and operating costs, both of which are far greater than the current cost of electricity supply. However, it was found that the opportunity for increased platinum beneficiation to support fuel cell technology lies in other applications of fuel cells, such as vehicles and mining machinery. The mining industry, which has increased focus on amplified mechanisation and modernisation, and the bus system, have been identified as malleable conduits through which fuel cell technology can be investigated for application in South Africa.

It has been concluded that the prospects for increased resource-led industrialisation through fuel cell manufacturing are incipient, in that the South African government, academia and industry have laid the foundation on which a manufacturing industry can be developed. Several competencies such as skills, capital investment and research and development will need further and continued attention. These prospects will be greatly advantaged by the sustained and increased support of government departments, and close collaboration between industry, state, academia and original equipment manufacturers.

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I dedicate this research work to the Almighty God. I am beyond thankful for His unwavering sustenance and provision of strength and fortitude.

This undertaking was made an exceedingly bearable load as the result of the support and encouragement from several individuals in my life, and I cannot be grateful for the completion of this project without recognizing their endearing espousal: my parents, Mr. and Mrs. Tsietsi and Mapitso Letanta; thank you both for always supporting me and encouraging me to aim for greatness. My partner, Mpfumelo Mhlongo; I appreciate you for your unending reassurance and cheering. I am also thankful for the love and support of my immediate and extended family. This research work is also dedicated to them.

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Abbreviations and Acronyms

AFC	Alkaline Fuel Cell
AMPLATS	Anglo American Platinum Limited
ANL	Argonne National Laboratory
BRT	Bus Rapid Transit
CAGR	Compound Annual Growth Rate
CHIC	Clean Hydrogen In European Cities
CHP	Combined Heat and Power
COM	Chamber of Mines of South Africa
CSIR	Council for Scientific and Industrial Research
DMFC	Direct Methanol Fuel Cell
DMR	Department of Mineral Resources of South Africa
DOE	Department of Energy of South Africa
DST	Department of Science and Technology of South Africa
DTI	Department of Trade and Industry of South Africa
Eskom	Electricity Supply Commission
EU	European Union
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCTO	Fuel Cell Technologies Office
GUMP	Gas Utilisation Master Plan
HySA	Hydrogen South Africa
IDC	Industrial Development Corporation of South Africa
IMPLATS	Impala Platinum Limited
IPAP	Industrial Policy Action Plan
IPM	Isondo Precious Metals

JPY	Japanese Yen
MCFC	Molten Carbonate Fuel Cell
MINTEK	Council for Mineral Technology
MPRDA	Mineral and Petroleum Resources Development Act
MPRDAA	Mineral and Petroleum Resources Development Amendment Act
OEM	Original Equipment Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEM or PEMFC	Polymer Electrolyte Membrane or Proton Exchange Membrane Fuel Cell
PGM	Platinum Group Metals
REIPPP	Renewable Energy Independent Power Procurement Programme
SAASTA	South African Agency for Science and Technology Advancement
SCFM	Standard Cubic Feet per Minute
SEZ	Special Economic Zones
SOFC	Solid Oxide Fuel Cell
UK	United Kingdom
USA	United States of America
USD	United States Dollar
USDOE	United States Department of Energy
W	Watts
Wh	Watt-hours
ZAR	Zuid-Afrikaanse Rand (South African Rand)

1. Introduction

1.1. Introduction

The African Mining Vision, drafted in 2009 by the United Nations Economic Commission for Africa, highlighted the need to achieve sustainable socio-economic development for the African continent, primarily through resource-based industrialisation. In South Africa there is a need for employment generation and economic development. This need is acknowledged in the New Growth Path and National Development economic plans; which also identify the potential for economic stimulation through mineral beneficiation. Efforts for economic development have recently been undermined by unreliable and increasingly costly power supply and alternative sources are being looked to for power generation.

The purpose of this study was to investigate the feasibility of the growth of the use of fuel cell technology for energy generation and, in so doing, explore prospects for enhancing local beneficiation through local manufacturing. To determine the outlook of this feasibility, the framework of this research was to investigate the use of fuel cell technology to power two South African AngloGold Ashanti mining operations. These were Mponeng Gold Mine and Mine Waste Solutions. This study aimed to determine the viability of using fuel cell technology to power the two mining operations instead of using coal-generated electricity from the national electricity grid as is currently done. An additional aim was to explore the possibilities that exist for platinum beneficiation to be enhanced through the localisation of fuel cell manufacturing. The importance of this research lies in the fact that the country is in need of economic stimulation as evidenced by the slowing and, in some cases, negative economic growth that was seen in 2016. As a nation that is rich in mineral wealth, there lies an opportunity for resource-based industrialisation to be enhanced and the avenue of fuel cell technology is one which can be explored. This potential for resource-led industrialisation is of current interest, as is the topic of industrialisation as a mechanism of economic growth. The latter topic is significantly focussed on in the national economic development plans, the New Growth Path and the National Development Plan.

Industrialisation is one of the most efficient ways in which the economy of the nation can be strengthened and economic diversification away from mineral resources can be attained, thereby reducing the dependence of the nation on its mineral wealth. The suggestion is not to do away with the extractive industry, but to enhance the economic performance of the nation through further industrialisation with the expectation that this improvement in performance will have a host of positive multiplier effects such as employment creation, poverty reduction and economic development. It is unrealistic and unsustainable to expect that the extractive industry should be solely relied upon for these objectives. This is partly because of the current state of commodity prices and how this has adversely affected the extractive industry, domestically and globally; and also because of the wasting nature of mineral resources and the resultant need to secure inter-generational sustainability. Further industrialisation is a more sustainable opportunity to bolster the nation's economic performance.

1.2. South African Economy

The incidence of a resource curse; which can be defined broadly as the existence of entrenched poverty despite the existence of mineral wealth and extraction in a nation (Elbra, 2013); in South Africa is debatable. However, the indicators pointing towards sluggish economic growth are irrefutable. The South African economy is categorized as an upper-middle income economy which is industrialised (Elbra, 2013). However, steadily increasing unemployment figures (Figure 1.1), further undermining poverty reduction efforts and increasing income inequality; indicated by a Gini index which has increased sharply post-1994 (Figure 1.2); all point towards a strained domestic economy.

Figure 1.1: Unemployment rate of South Africa from 2001 to 2017 (Modified from Trading Economics, 2017c)

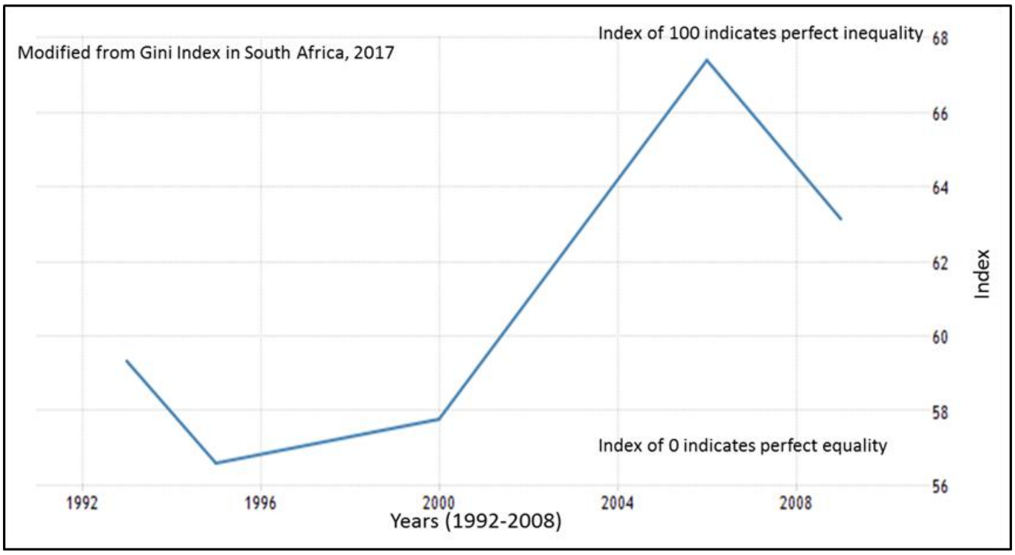


Figure 1.2: Gini Index of South Africa from 1992 to 2008 (Modified from Trading Economics, 2017a)

Post-Apartheid unemployment in South Africa reached a peak in the first quarter of 2003 at 31.2% and started a significant decline thereafter, attaining low levels of 21.5% in the first quarter of 2008 (Trading Economics, 2017c). The decline in the unemployment rate coincides with the economic growth that was occurring at that time. The country's Gross Domestic Product (GDP) growth rate, which represents the rate at which an economy grows or contracts, was positive and steadily rising until it fell sharply and even became negative after the onset of the global financial crisis in 2008, reaching a low of -6.10% in the first quarter of 2009 (Trading Economics, 2017b). The Industrial Development Corporation (2013) corroborated the link between rising GDP growth rate and increased economic activity in the period of 2003 to 2007, where it observed that the construction sector grew significantly due to the increased demand for residential buildings and non-residential construction and boosted economic activity even further. Since 2008, the unemployment rate has steadily increased and, in 2016, it reached 27.1% in the third quarter of 2016 (Reuters, 2016). The sudden increase in unemployment in 2009 coincides with the global financial crisis that took place at around the same time. The contraction of several South African industries such as mining, manufacturing and agriculture can be considered to have contributed to the increasing unemployment rate in recent years (Reuters, 2016). Harmse (2013) suggested that the significant contributor to the high levels of inequality is attributable to the lingering, generational effects of the segregation policies of South Africa's apartheid regime. Additional factors, such as poor education policies and their implementation and large-scale unemployment were also cited. Although there is a lag in the time between the trends in unemployment and inequality (indicated by the Gini coefficient), there is an observable coincidence with an increasing inequality trend in 2003 with the high unemployment rate that was recorded at the time. Inequality began to decline suddenly in 2006 and this could be attributed to the effects of the economic growth which had reached a significant high around that period.

According to Business Dictionary (2017), industrialisation is the progression through which conventionally non-industrial sectors of an economy become more comparable to the manufacturing sector of the economy. Invetsopedia (2017) defined the hallmarks of industrialisation as economic growth and the increased reliance on innovation in technology to solve problems rather than reliance on conditions beyond human intervention. Several iterations of the national economic development plans are significantly cognisant of the pressing need for and the challenge of creating sustainable economic development and suggest further industrialisation as one of the vehicles with which to attain this development. Morris and Fessehaie (2014) echoed the sentiments that efforts towards industrialisation not only stand to create employment and fight poverty, but will also foster skills development, technological innovation, capital accumulation and the intensification of knowledge. The creation or enhancement of forward linkages through mineral beneficiation can aid these efforts. Szirmai (2011) suggested that the empirical evidence from literature for the relationship between the level of industrialisation and the per capita income in developing nations is sufficient to determine that industrialisation is a significant driver of economic development.

1.3. Importance of Electrical Energy in the South African Economy

Some of the sectors which drive the economy, such as mining and manufacturing, are energy intensive (Brand South Africa, 2015). Bohlmann, et al. (2015) discussed the energy supply crisis that the country faced in 2014 which led to power-cuts and necessitated an increase of electricity supply for economic growth and development to be supported and facilitated. Research that was conducted by Bohlmann, et al. in 2015 indicated that South Africa’s economic growth would be greatly disadvantaged in the absence of the additional power generation capacity which was scheduled to be brought online through two of the national energy supplier’s new coal-fired power stations, Medupi and Kusile. Findings also suggested that, by 2015, insufficient power supply had already contributed to significant loss and damage to the country’s economy through billions of Rands, an estimated 300 billion South African Rands (ZAR) since 2008 (BusinessTech, 2015). Brand South Africa (2012) noted that the imbalance between an increased demand and limited supply was spurred by growing industrialisation, significant economic growth and a large-scale electrification programme while citing underinvestment in power capacity infrastructure as a reason for electricity demand rising faster than it could be met. Through employment creation and multiplier effects, electricity power stations also contribute to the economy. The Koeberg nuclear power station in the Western Cape contributed ZAR23 billion to South Africa’s economy from 2013 to 2016 (Peyper, 2017).

Also pertinent to the discussion around electricity and the domestic economy is coal as the country’s main source of energy, which provides for 77% of South Africa’s energy requirements (Statistics South Africa, 2015). Coal not only provides energy, it is also a source of employment and economic growth, having contributed ZAR51 billion to the economy in 2013 (Statistics South Africa, 2015).

1.4. Electrical Energy

The energy system primarily relied upon in South Africa is domestic coal with limited wind and solar photovoltaic energy available as renewable energy supply, and natural gas obtainable in little quantities (Bischof-Niemz, et al., 2016). Coal, as a significant source of electrical energy in South Africa and the world, has been made use of because of its ease of mining and low cost and makes up around 36% of electricity generation worldwide and 77% domestically (Eskom, 2017a). An electric current is produced and distributed through power lines when ground coal is blown into boilers and the heat in the boilers causes the coal particles to combust and transform water into steam. This steam then propels a turbine, which turns a copper wire coil within a magnet. These components constitute a generator which produces an electric current (Eskom, 2017a). As has been widely discussed, coal bears a significant amount of responsibility for the emissions that are responsible for climate change and there has been a momentous drive worldwide to find alternatives, particularly in renewable energies. In addition, the efficiencies of coal powered stations are only slightly more than 30% (de Vos, 2017). 4th Energy Wave (2015) stated that 15% of the world's entire water extraction goes towards the energy sector, with coal and nuclear taking up the bulk of this water. This is something that has significant implications if the current global drought trends are to be considered. South Africa is one of the countries which ratified the Paris Agreement on Climate Change in 2016, signifying a commitment to addressing climate change and its effects. The Paris Agreement, a legally binding agreement, allows the world's nations to converge in a common goal of addressing climate change (Department of Environmental Affairs of South Africa, 2016).

Where renewable energy has been considered, wind, solar, tidal and hydro-power have been considered as options. Wind power results when windmill blades, which are connected to generators, capture wind energy and produce electricity (Eskom, 2017b). It is acknowledged by Wind Energy Technologies Office (2017) as being a sustainable and renewable low priced energy source which is clean and has no polluting effects that are seen with emissions from other fuel sources such as coal or gas. However, the initial investment for wind power is still higher than what would be required for traditional fossil-fueled generators and there have been concerns over the impact that wind turbines have on wildlife as birds flying into these turbines are killed (Wind Energy Technologies Office, 2017). Furthermore, the instability of wind means that it is not a reliable source to meet baseload energy demand unless there is a form of energy storage used in conjunction with the energy generation, such as batteries (Maehlum, 2015).

Solar energy relies on the conversion of energy from the sun into electrical energy and, like all other forms of renewable energy, is free of pollutants or emissions while reducing reliance on fossil fuels. Solar panels are also very low maintenance and have a lifespan exceeding thirty years (Solar Electric Power Company, 2012). Their challenges, like wind power, include high initial investment costs and a lengthy payback period, as well as difficulties that arise from the variability of natural cycles. Cloudy and winter days see less electricity generation and there is a need for energy storage for the period between sunset and sunrise (Solar Electric Power Company, 2012).

Water is also used for energy generation, whether in the form of hydro-power energy or tidal energy. Hydro-power energy involves the release of water to drive turbines which are connected to electricity producing generators and electrical energy is sourced from tidal waves when these waves drive turbines which are also connected to generators (Eskom, 2017b). Hydro-power plants require the construction of dams, which can only be built in suitable locations, and have high capital costs and high lead times. Although, once operational, they have very low operating and electricity costs and no further expenses (Shah, 2011).

Tidal energy is more predictable as an energy source, as tides have a relationship with the moon, and tides have a higher energy density than the other natural energy sources. However, it is a development which also has high initial investment costs and an efficient energy storage is required as tidal energy is only produced during tides, which are cyclical. There are also concerns about what disruptive effects the tidal power plants could have on marine ecology (Tutorials, 2017).

A contentious topic of South African energy has been nuclear power, a controversial matter because of the estimated cost of nuclear energy procurement being placed at ZAR1 trillion at a time when the domestic economy has been underperforming. Nuclear power has been made use of in South Africa in the Western Cape province, where a nuclear reactor produces 5% of South Africa's energy and has been in production since 1984 (World Nuclear Association, 2017). Where nuclear energy is used to generate electricity, heat that is released in a nuclear reaction is used to heat water and turn it into steam and this steam is used to rotate turbines connected to a generator. In as much as nuclear energy produces less greenhouse emissions than fossil fuels, the environmental impact that the mining and processing of uranium has, as well as the disposal of radioactive waste, would be at odds with the alternative energy sources that are deemed more favourable in efforts to produce clean energy (Conserve Energy Future, 2017). Additionally, nuclear accidents, the most recent being in Fukushima in Japan in 2011, have been catastrophic, with extended effects on the environment and humans. Lastly, natural gas has also been looked to as an alternative to coal for energy, with South Africa dependent on imports of natural gas from Mozambique.

Eurelectric (2003) compiled knowledge on the efficiencies of various energy sources, as a function of the efficiencies of the conversion of various types of energy into electrical energy, some of which have been discussed. Fuel cells, which are discussed in further detail in the following section, were placed in efficiencies at or greater than 40% (Figure 1.3) .

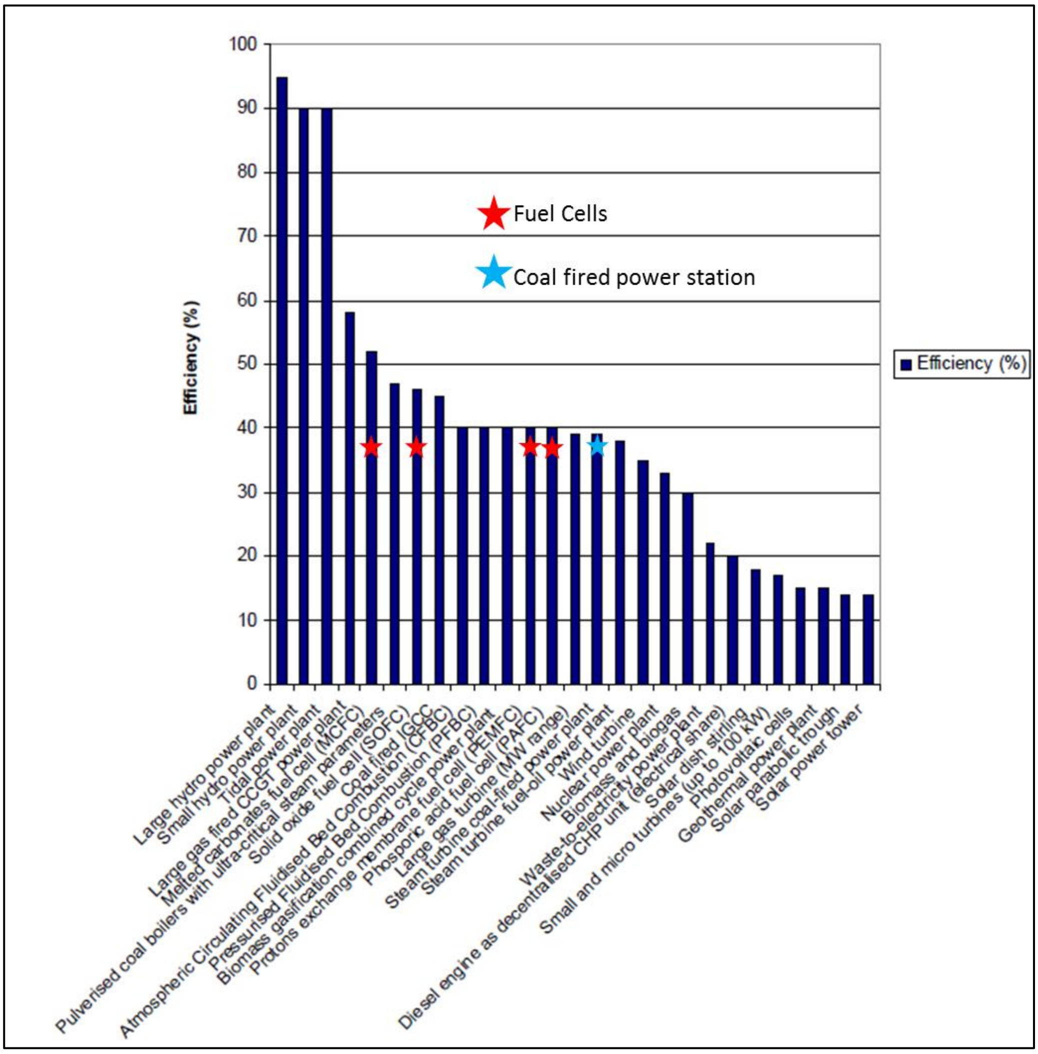


Figure 1.3: Efficiencies of various sources into electrical energy (Modified from Eurelectrics (2003))

1.5. Research Motivation

This research will improve understanding in the subject of mineral beneficiation in South Africa as well as the topic of resource-based industrialisation. There is an opportunity for additional knowledge in the scope of local beneficiation of mineral resources and the degree to which forward and backward linkages can be augmented should be explored. An adjuvant motivation for this research pertains to the lack of significant national economic development (marked by increasing unemployment and income inequality), despite the mineral wealth that the country holds and the minerals-based nature of its economy. The need for increased mineral beneficiation falls in line with the national objectives of sustainable development and a study of this nature will contribute towards the exploration of one prospective avenue of sustainable development. Successful local adoption and growth in the use of fuel cell technology for energy may act to catalyse local manufacturing and could potentially also result in significant contribution towards the diversification of the South African economy away from the dependence on traditional export of mineral resources, and, thus, shield it to some degree from commodity price volatility. Therefore, the degree to which fuel cell technology has the potential to become a substantial source of reliable, clean energy, while simultaneously contributing to the domestic economy through local manufacturing ought to be scrutinised.

This particular research may aid policymakers, predominantly those of mineral and industrial policy, in ways to facilitate increased downstream beneficiation of mineral resources. Industrial policy cannot be effective when enacted in isolation and a co-ordinated effort is required from partner ministries, particularly those of economic development, science and technology and mineral resources. Therefore, a wide range of policymakers would benefit from taking an all-inclusive approach to designing policy in order to avoid the frustration of contradictory policy interventions across ministries. The findings of this research may also aid fellow researchers in the practical ways in which fuel cell technology can be used.

This study may also provide insight into possible alternative sources of energy amidst the nation’s energy supply crisis. The two operations that were considered for this study were selected primarily due to the relatively longer lives that they are anticipated to have within the South African region of AngloGold Ashanti Limited and the resultant opportunity that the long lives would offer for the observation of the outcomes of any technological innovation to be made. The South African economy is a minerals-based one and, consequently, the strengthening of the mining industry is in the best interest of the domestic economy. Increasing operating costs are a concern for South African mining operations (South African Broadcasting Corporation, 2017), thus, highlighting the need for justifiable solutions to be considered.

1.6. Research Objectives, Methodology and Limitations

The objectives of this research were to ascertain the feasibility of the use of fuel cell technology for power generation on two AngloGold Ashanti mining operations and the prospects that exist for local platinum beneficiation through local fuel cell manufacturing. The sites selected for study are a South African deep-level gold mine and its plant (Mponeng Mine) and a surface operation (Mine Waste Solutions).

The methodology that was applied for this research involved:

1. A detailed scrutiny on fuel cell technology and its development in several regions around the globe, and the work that was carried out by the leading nations in order to support advancements in the technology. The findings of this analysis would assist in determining the key foundations required in supporting and growing a nascent fuel cell industry domestically;
2. A cost analysis of establishing and maintaining a fuel cell power station for the two mentioned mining operations. The costs were divided into capital costs associated with acquisition and the operating costs;
3. An analysis of the proficiencies that need to be developed for the localisation of fuel cell manufacturing to be accomplished, as well as the platinum beneficiation that could result from the localisation; and

4. A study into the compatibility of a localisation endeavour with current mineral and industrial policies.

The limitations of this study are that this study only pertained to the economic feasibility of acquiring a fuel cell for the mining operations. The technical feasibility of establishing the fuel cell power stations was not tailored for herein, nor was there any consideration of specialist intricacies that would have to be made when contemplating the installation of a fuel cell.

1.7. Research Localities

AngloGold Ashanti's Mponeng mine is situated some 80km south west of Johannesburg (Figure 1.4) and it is a deep level gold mine reaching depths of 3 900m, with intentions to deepen the operation even further. The deepening projects were expected to extend the operation's life to the year 2040 (Mining Technology, 2013). However, since the commencement of this study, AngloGold Ashanti has announced its intentions to restructure several of its business units in an effort to curb unsustainable losses that have been incurred in its South African region. One of the phases of Mponeng Mine's deepening projects that would have extended the operation's life until 2040 has had to be revised until a more optimal option of deepening access to the orebody can be attained (Creamer, 2017c). Since Mponeng Mine and its gold plant are billed together on a single billing account section, the study site encompassed both mine and plant, which are referred to henceforth as the Mponeng Complex in this study.

Mine Waste Solutions is situated in the North West Province, approximately 8km from the town of Klerksdorp. This surface operation delivers gold by processing low-grade stockpiles from surface material (Barradas, 2016) and is expected to be in operation for the next thirty years and beyond (PR Newswire, 2012). It is unclear at this stage how AngloGold Ashanti's restructuring process will impact upon Mponeng Mine and Mine Waste Solutions' lifespans.

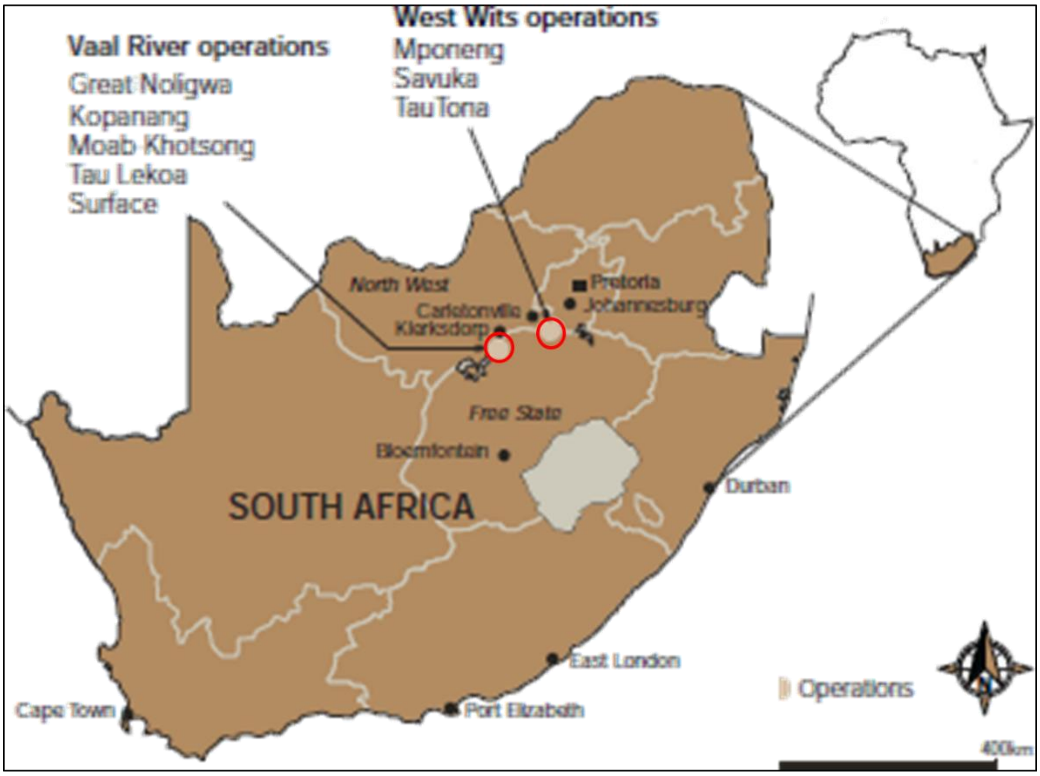


Figure 1.4: AngloGold Ashanti Limited South African Operations (Modified from Janitch, 2014)

1.8. Structure of the Report

This report is divided into six chapters. The overview of each chapter is presented below.

Chapter One: This introductory chapter encompassed the general background of the subject matter, with a review of the position of the nation where pertinent factors, such as economics and electricity, are concerned. The context and setting of the research were established, and details of the methodology and research localities were laid out.

Chapter Two: Fuel Cell Technology is discussed in greater detail in this chapter, with an elaboration on various types of fuel cells and their workings, followed by platinum beneficiation in the context of fuel cells. The uses for electricity in mining and the applications of fuel cells that have been advanced in mining are also discussed and, finally, an observation of the market trends of fuel cells is made.

Chapter Three: This chapter details the expansions made in fuel cell technology in recent years, where a significant increase in adoption, manufacturing and exportation has been observed. The efforts made by each of the nations where these advancements have been greatest are singled out for discussion so that the most applicable lessons from these regions can be highlighted.

Chapter Four: This chapter is a compilation of the findings of the cost analysis of the construction, operation and maintenance of a fuel cell power station, along with the possible options for financing that could be considered for such an endeavour.

Chapter Five: In this chapter, the practical feasibility of establishing and operating a fuel cell power station, with all considerations made in the preceding chapter, are discussed. An additional facet of this discussion is to identify the prospects that South Africa has for localisation of fuel cell manufacturing and the work that would need to be put in for this potential, if any, to be realised. Foreseeable challenges and possible mitigation strategies in this regard are deliberated and, finally, the impact that such an undertaking could potentially have on beneficiation in South Africa is discussed.

Chapter Six: Conclusion and recommendations. This chapter encompasses a summary of all of the preceding chapters and a conclusion of the findings of the research. Recommendations for additional work on this particular research topic are made.

1.9. Conclusion

This chapter highlighted the need for the stimulation of the domestic economy, and focus on resource-led industrialisation was cited as one of the avenues through which this stimulation could be attained. The context, relevance and methodology of this study were framed, along with the structure of the research. The important relationship between electrical energy and the economy was also highlighted.

The point of the context setting of this research was that resource-led industrialisation through the prospect of increased platinum beneficiation is an option that ought to be considered as a possible solution to the persistent domestic economic underperformance that has prevailed of late. The mining industry is still a considerable contributor to the South African economy and is facing cost pressures due to increased electricity costs, which account for a high proportion of the operating costs. There is a potential benefit for local platinum beneficiation, the South African mining operations and potentially the domestic economy at large that could be seen with the implementation of alternative energy sources, particularly fuel cells.

The next chapter will go into further detail about the most common types of fuel cells, their global markets and the applications in which they are generally used. The use of platinum and the associated beneficiation will also be conferred.

2. Fuel Cell Technology

2.1. Introduction

Fuel cells are much more efficient than internal combustion engines, with the former reaching efficiencies of 50-60% and the latter averaging 20% (Hydrogen London, 2015). The capacity of fuel cells can range in size from powering cellular phones and vehicles to a whole neighbourhood, with capabilities to be used as separate power sources or in connection with existing electricity grids (New Energy World, 2011). Heat is also generated as a by-product of the power generation and can be utilised for heat provision for buildings (South African Agency for Science and Technology Advancement, 2015). According to New Energy World (2011), fuel cells have the broadest set of applications than all other presently obtainable power sources, being useful in a wide range of portable, stationary and transport applications.

The South African Agency for Science and Technology Advancement (2015) acknowledged that fuel cells are not without their challenges. The biggest obstacle is their high cost of production and mass production. The reduction in the cost of their catalyst (which is often platinum) will, therefore, be required in order to make them competitively affordable. Another challenge lies in the need for linkage development with other South African industrial manufacturers for the development of fuel cell technology.

According to the South African Agency for Science and Technology Advancement (2015), there is an increasing need to look to alternative, renewable energy sources as the current burning of fossil fuels (coal, natural gas and oil) has sparked significant environmental concerns. Such concerns include global warming as the result of heat being trapped near the earth’s surface by methane, carbon dioxide, water vapour and nitrous oxide. The South African Agency for Science and Technology Advancement (2015) further indicated that the expectation is that the global population's energy demands will soon be too great to be met by fossil fuels. Van der Zee (2014) stated that electricity costs for South African industries have undergone a 178% increase for the period 2007 to 2012.

This chapter details several different types of fuel cells and the relevance of this technology to South African platinum beneficiation. This chapter will also detail the various uses of electricity on a mine and the applications that have already been explored for fuel cells in mining. It is also important to gain an understanding of the characteristics and trends of the global fuel cell market, which will assist in appreciating future expectations for the technology.

2.2. Fuel Cell Types

2.2.1. Proton Exchange Membrane or Polymer Electrolyte Membrane (PEM) Fuel Cells (PEMFC)

Energy is generated by a fuel cell when electrochemical reactions take place in the presence of a platinum catalyst to convert potential chemical energy into electrical energy and could run indefinitely; provided that it has sufficient supplies of hydrogen and oxygen (Fuel Cell Today, 2017). Hydrogen and oxygen are combined in a fuel cell, through the electrochemical reaction of the two, to produce electricity, heat and water and the process produces neither emissions nor pollutants (Hydrogen London, 2015). The fuel cell comprises an electrolyte positioned in between two electrodes (a cathode and an anode, both coated with a catalytic substance) with connectors in order to gather the produced current. A stack results when a number of these cells are connected in series to obtain increased power output (Hydrogen London, 2015). At the boundaries between the three segments, two chemical reactions take place. Hydrogen and oxygen are introduced to the opposite sides of the partitioning proton exchange membrane. The catalyst on the anode breaks the hydrogen molecules into electrons (negatively charged ions) and protons (positively charged ions) (South African Agency for Science and Technology Advancement, 2015). The protons move through the membrane to the oxygen on the other side, where they react at the cathode catalyst with the oxygen to form water. But the electrons are not able to pass through the membrane, so they flow through an external circuit instead and create an electrical current which results in a power source (Figure 2.1) (South African Agency for Science and Technology Advancement, 2015).

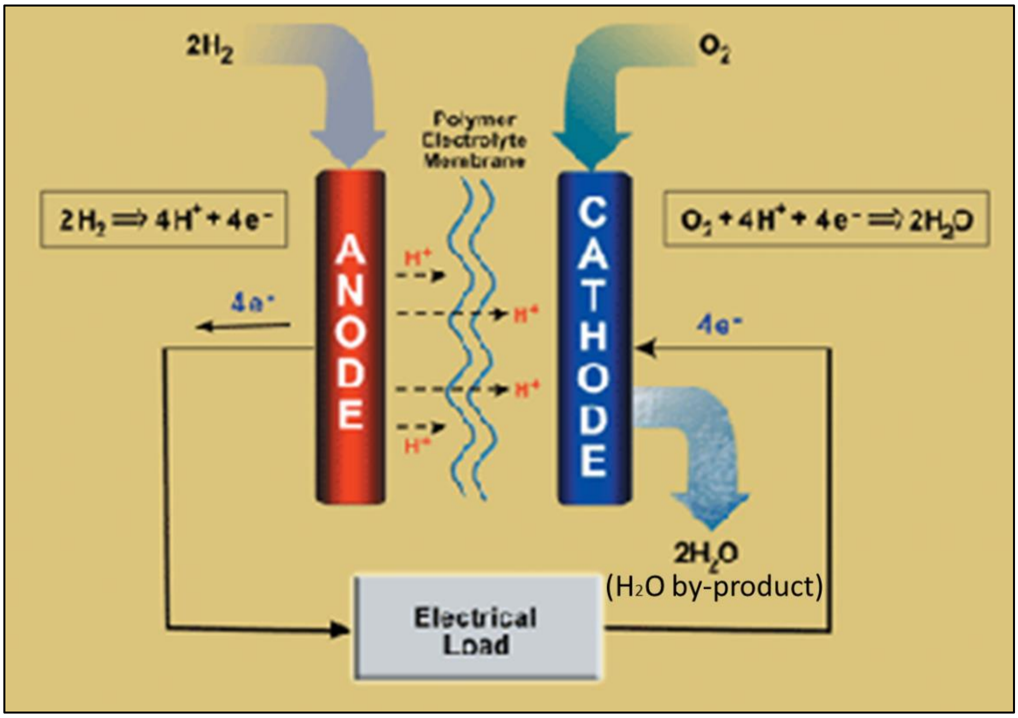


Figure 2.1: Simplified illustration of the workings of a PEM fuel cell (Modified from United States Environmental Protection Agency, 2016)

2.2.2. Solid Oxide Fuel Cells (SOFC)

The SOFC is another type of fuel cell, an all-solid-state fuel cell centred on an electrolyte which is a solid oxide (Zuo, et al., 2012). It is commonly used in big, high-power applications such as large-scale electricity generating stations. These fuel cells operate at very high temperatures of 600°C to 1000°C and have typical efficiencies reaching 70%; making them the most efficient fuel cell type in terms of energy generation (Fu, 2014). It is at this high temperature that heat can also be produced as a by-product, allowing for co-generation and combined cycle applications. They also produce low emissions like their PEM counterparts and can be fuelled with natural gas (Fu, 2014).

The construction of a SOFC involves two electrodes located on either side of a hard ceramic, solid oxide electrolyte such as zirconia and a gas such as hydrogen is supplied to the anode of the cell while oxygen is introduced through the cathode (Figure 2.2) (Fu, 2014). The electrolyte between the electrodes acts as an ionic conductor, and it ought to be an electronic insulator and impermeable to gas (Zuo, et al., 2012). Hydrogen gas is fed onto the anode’s surface and electrons are conducted from the electrons that are liberated from the hydrogen molecule. These electrons are directed to the external circuit and used as power. Meanwhile, at the cathode, oxygen is introduced and conducts electrons back from the external circuit and, upon being recombined with oxygen ions transferred through the electrolyte, combines with hydrogen to produce water (Fu, 2014). Hydrogen, carbon monoxide and methane can be used to fuel the SOFC (Chick, 2011). The SOFC is different from other fuel cells in that it does not require pure hydrogen as a fuel and almost any hydrocarbon can be used to fuel it (Grolig, 2013).

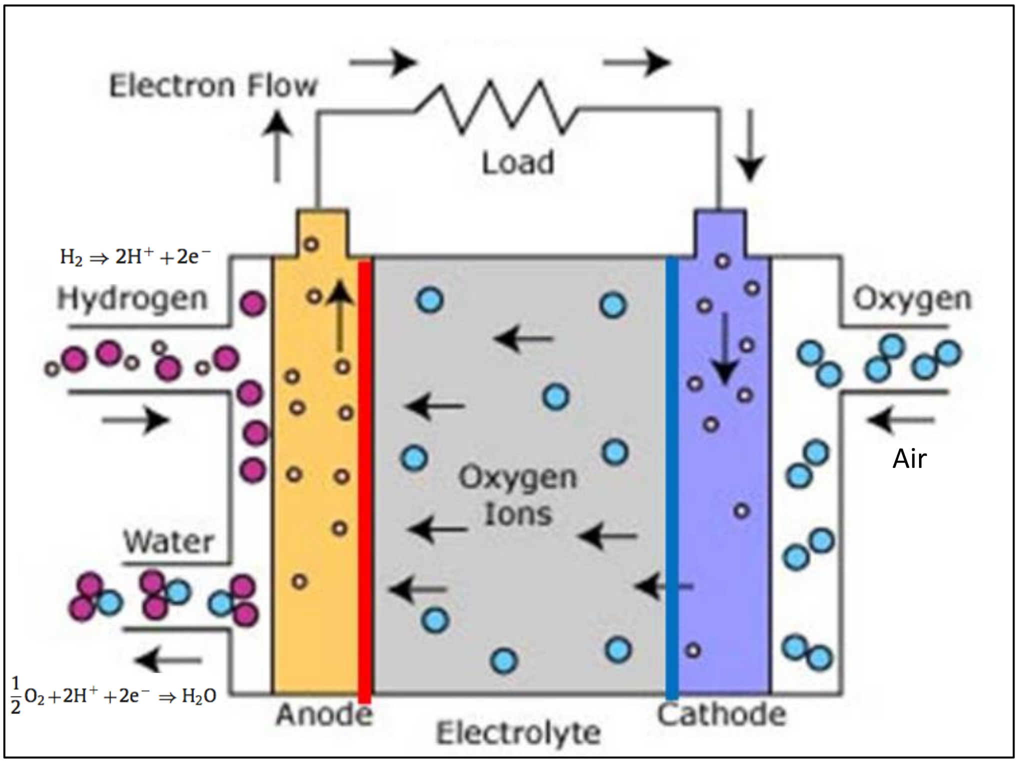


Figure 2.2: Typical solid oxide fuel cell (Modified from Fu, 2014 and Jazouli, 2016)

As already mentioned, a SOFC has the additional advantage of co-generation and from its heat, heating and cooling applications can be utilised. In this instance, absorption chillers are used to make use of heat as an energy source instead of electricity (Chen and Ni, 2014). This, thus, creates the opportunity for multiple uses to be drawn from the SOFC: electricity generation, heating and cooling.

2.2.3. Molten Carbonate Fuel Cells (MCFC)

MCFCs, which operate at temperatures averaging 650°C to 800°C, are so named because of the carbonate salts which they use as an electrolyte, which are usually made from lithium and potassium carbonate (Takizawa, 2017). These carbonate salts turn to a molten state when heated to a high temperature (McVay, 2014). The high operating temperatures also mean that

MCFCs are able to convert hydrocarbon fuels into hydrogen within the fuel cell, which is referred to as “internal reforming” (Fuel Cells 2000, 2017). These fuel cells have an efficiency of 60% which can be increased to 80% if combined heat and power (CHP) applications are made use of (Smithsonian Institution, 2001). At these temperatures, nickel is more commonly used as a catalyst and not platinum. The nickel allows for the use of a reformed gas from hydrocarbon fuels, which allows for a wide range of fuels to be used (Takizawa, 2017). A ceramic mesh is used to brace the electrolyte and this allows for the integrity and structure of the electrolyte to be retained during operation and downtime (McVay, 2014). The high operating temperature of the MCFC also means that it, too, can be used in CHP applications like the SOFC. Its operations at lower temperatures than those of the SOFC means that it does not require the materials required by the SOFC, making its design a little less expensive (The Chartered Institution of Building Services Engineers, 2012).

The MCFC does not traditionally use platinum in its electrodes. However, Wyatt and Fisher (1988), suggested that platinum, along with other platinum group metals (PGM) could be used in the anode components in order to control the corrosion that is common with the MCFC as a result of the corrosive nature of the molten carbonate. Work carried out by Wyatt and Fisher (1988) showed that the PGM offer confidence in being corrosion-resistant. It should be noted that early MCFCs had platinum, palladium and palladium-silver alloys making up their anodes, but these types of anodes were done away with in order to reduce the cost of the fuel cell (Wyatt and Fisher, 1988). Another opportunity for the use of PGM is in reformation technology (Isondo Precious Metals, 2017).

The complete electrochemical reaction produces water from hydrogen and oxygen and, at each electrode, a half-reaction takes place (Figure 2.3) (Takizawa, 2017). The MCFC has been successfully used in stationary applications and distributed power generation and is well suited to large or industrial sites for baseload power generation (Allen, 2012). With a MCFC, carbon oxides can be used as fuel, which entails opportunity for fuelling with gases derived from coal, as they are more resistant to the contaminants that arise from carbon oxides.

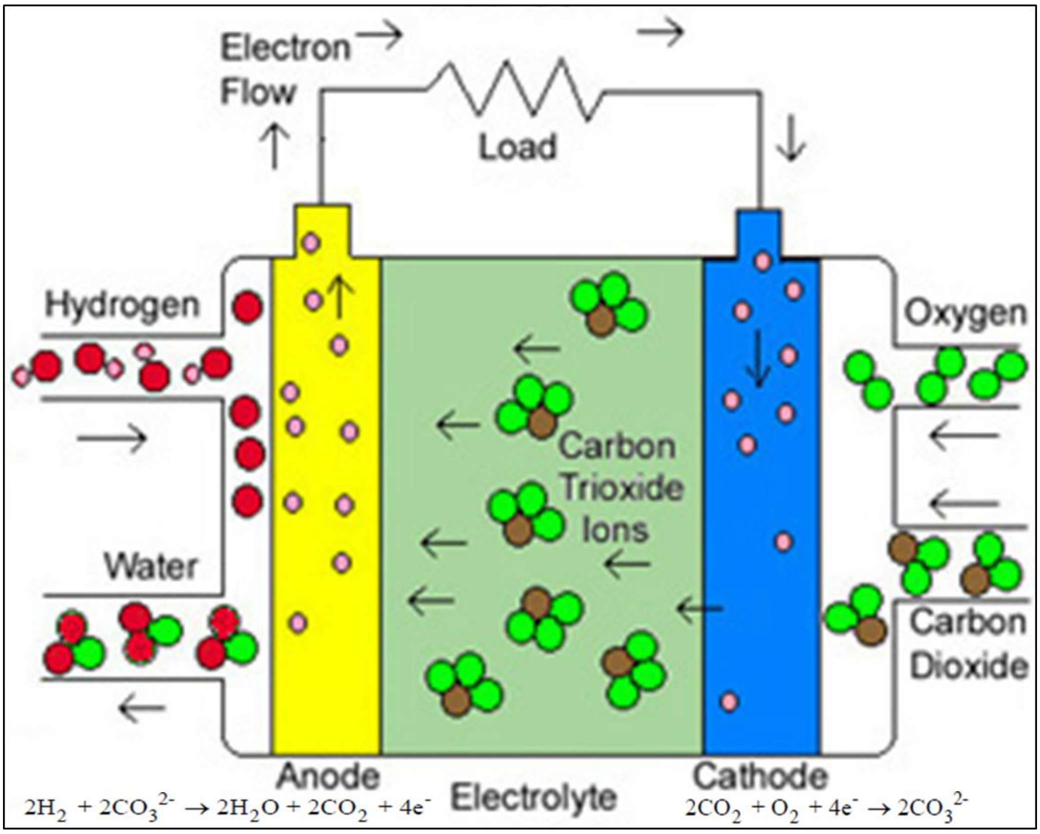


Figure 2.3: Typical Molten Carbonate Fuel Cell (Modified from Smithsonian Institution (2001) and Takizawa (2017))

A complete fuel cell power plant for stationary applications includes a fuel processor, a fuel cell power section and a power conditioner (Figure 2.4). Natural gas is fed into the fuel processor, where it is converted into a hydrogen-rich gas, which is what fuels the fuel cell. This gas is then passed into the fuel cell power section, which contains the fuel cell stack. Electrical power is generated in the fuel cell power section in the form of direct current (DC), and it is transferred into a power conditioner where it is transformed into alternating current (AC) power (Remick and Wheeler, 2010).

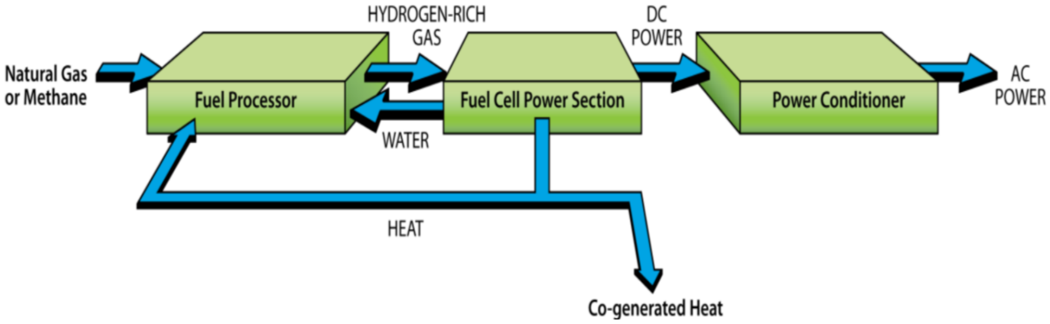


Figure 2.4: Fuel cell power plant and its components (Remick and Wheeler, 2010)

2.2.4. Other Fuel Cell Types

Other common fuel cell types include the direct methanol fuel cell (DMFC), a fuel cell which has operating temperatures of 60°C to 130°C and which incorporates platinum in its system. Like the PEMFC, it makes use of a polymer membrane for its electrolyte and relies on methanol as a fuel (Fuel Cell Today, 2018b). Methanol is a relatively cheaper fuel and has a higher energy density. The DMFC is commonly used in applications having low power requirements, examples being portable power packs and mobile electronic devices, as well as material handling vehicles like forklift trucks (Fuel Cell Today, 2018b). The Alkaline fuel cell (AFC), which utilises an alkaline electrolyte like potassium hydroxide and nickel as a catalyst instead of platinum, has been used primarily in spacecraft for electricity and water production on space shuttles, with minimal use in commercial applications (Fuel Cell Today, 2018a). Phosphoric acid fuel cells (PAFC) make use of liquid phosphoric acid as an electrolyte and are commonly used for power generation in buildings. They have the advantage of being able to efficiently cogenerate heat as well as the ability to make use of impure hydrogen for fuel, which expands the selection of fuels that they can utilise (AZo Cleantech, 2018).

2.3. Platinum Beneficiation and Industrial Policy

South Africa's beneficiation strategy, drafted by the Department of Mineral Resources (DMR), acknowledged that, although there have been strides in local mineral beneficiation in mineral processing, there remains room for significant value addition in mineral development through exporting high-value products (Department of Mineral Resources of South Africa, 2017). The aim of the strategy is to facilitate the value addition of South Africa's mineral resources by enhancing local beneficiation initiatives to the final phase of the value chain. The strategy has also stated alignment with a national industrialisation programme, whose goals include augmenting the quality and quantity of exports, creating employment, promoting a green economy and attaining economic diversification. Furthermore, the need for collaborative efforts across different ministries, including Economic Development, Trade and Industry, Public Enterprises, Science and Technology, National Treasury and Energy, as well as the mining industry and labour were highlighted as being necessary for executing an effective beneficiation strategy (Department of Mineral Resources of South Africa, 2017). Importantly, PGM fuel cells were touted in the beneficiation strategy as one of the levers with which greater value beneficiation can be achieved; with the potential for global fabrication and supply of fuel cell components being recognised. What is important to note is that the opportunity for job creation increases with the degree of value addition along a mineral value chain (Figure 2.5).

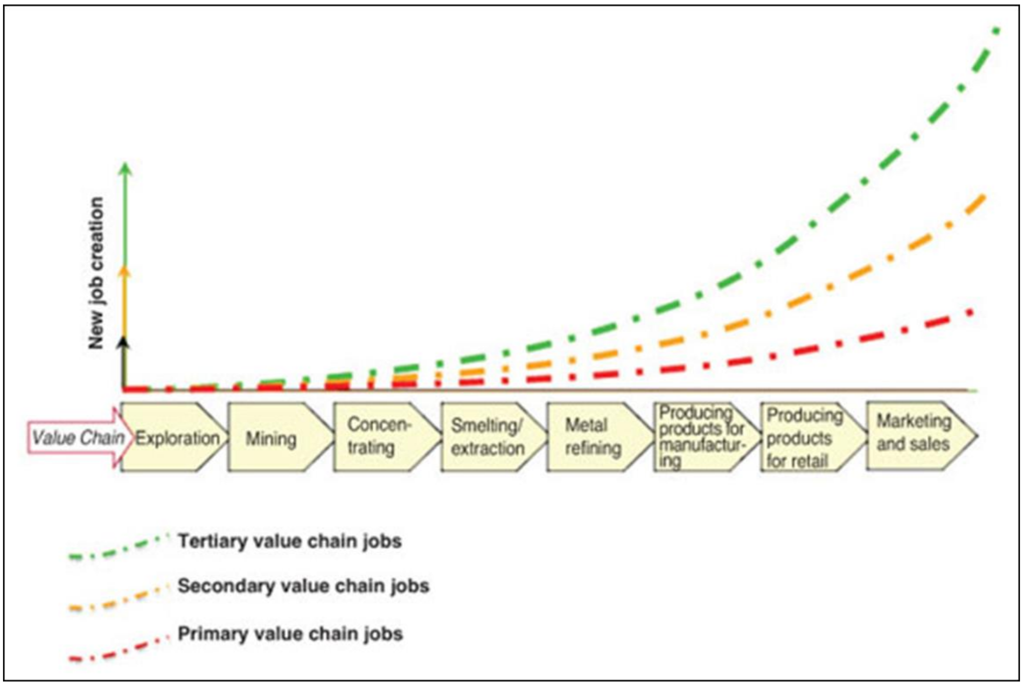


Figure 2.5: Mineral value chain and associated job creation (Rossouw and Baxter, 2011)

According to Rossouw and Baxter (2011), 87% of the world's PGM are in South Africa, and this augments the comparative advantage that would set the groundwork for platinum beneficiation through fuel cell technology. The current policy and legislative framework would also be supportive of such an endeavour. The Mineral and Petroleum Resources Development Act 26 of 2002 (MPRDA), the Precious Metals Act and the South African Mining Charter are supportive of local beneficiation (Department of Mineral Resources, 2011). As it stands, there is already a considerable downstream beneficiation industry even though there is also a considerable skills shortage that must be addressed to make the shift from mining into higher-end value addition (Rossouw and Baxter, 2011).

One of the strongest influences regarding the success or failure of such an endeavour is the industrial policy. Londero and Teitel (1996) and Reinhardt (2000) as cited by Morris and Fessehaie (2014) attributed the successful exports of resource-based industries in several resource-rich nations such as

Thailand, Malaysia, Venezuela and Argentina largely to the economic policies that allowed for their accumulation and effective industrial policies and not so much on high levels of early skills and capital. According to Syrquin (2007) as cited by Ramdoo (2015), what industrial policy should aim to achieve is the enablement of foreseen structural change through the elimination of obstacles and the adjustment for market failures. In this context of resource-based industrialisation, Ramdoo (2015) suggested that the most effective policies are those that direct incentives and support programmes to possibly interested manufacturers and not necessarily towards miners.

Chang (1997:3) loosely defined industrial policy as “state intervention in industrial restructuring”, with sector-specific targeting as its focal point, and made the observation that industrial policy is largely about foresight for the future industrial formation of the economy and the co-ordination required to attain it. In post-Apartheid South Africa, there was a need for the creation of an industrial policy that would allow for an improvement in the living standards of the majority of South Africans to be made and for past gross economic imbalances to be rectified (Chang, 1997). The approach to industrial policy in South Africa has essentially been to implement a varied range of policies to endorse broadly defined sectors such as mining, infrastructure, resource-based industrialisation and manufacturing. The main components of the country’s current industrial policy are those such as investment facilitation, technology and innovation, trade, small business promotion, strategic and informational leadership, labour market policy and competition (Altman and Mayer, 2003).

The point of contention regarding the use of platinum in fuel cell technology is the significant bearing that it has on the increased capital cost of fuel cells. It has been cited as a reason for the cost barrier that exists to commercial viability (Sealy, 2008), and research is being carried out on ways in which the amount used can be reduced. Nevertheless, the amount of platinum used in

PEM fuel cells increased significantly from 2013, where the usage was less than ten thousand ounces to twenty-five thousand ounces in 2014. The expectation was that the usage would increase to thirty-four thousand ounces in 2015 (Figure 2.6) (4th Energy Wave, 2015). In reality, platinum demand in 2015 dropped to twenty-two thousand ounces from the fuel cell sector (4th Energy Wave, 2016). Where fuel cells are concerned, the greatest avenue for platinum beneficiation lies in PEMFC, PAFC and DMFC.

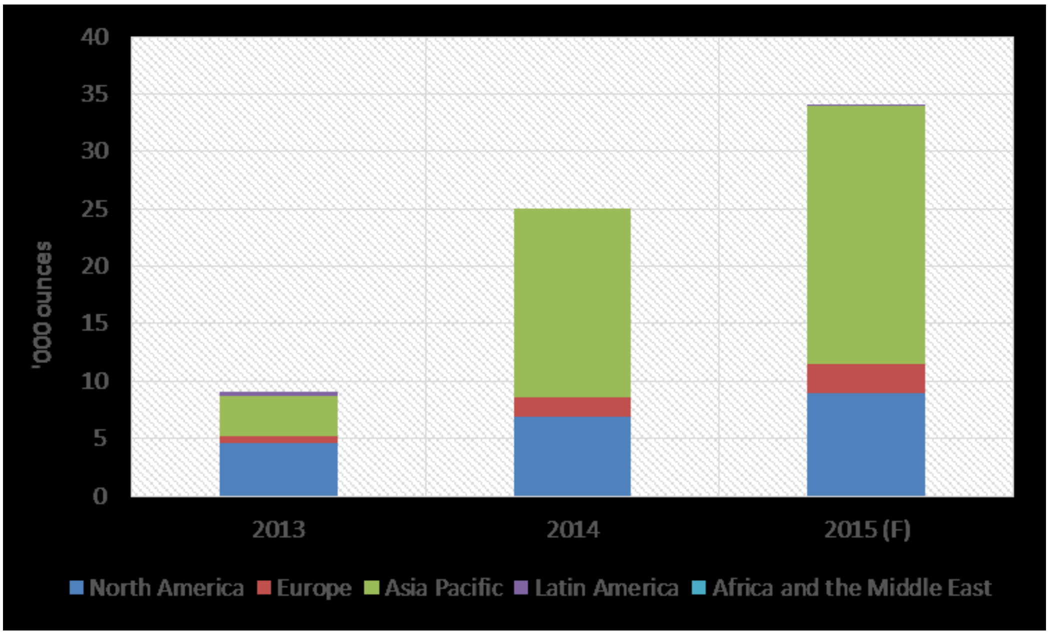


Figure 2.6: Global platinum usage in fuel cells (4th Energy Wave, 2015)

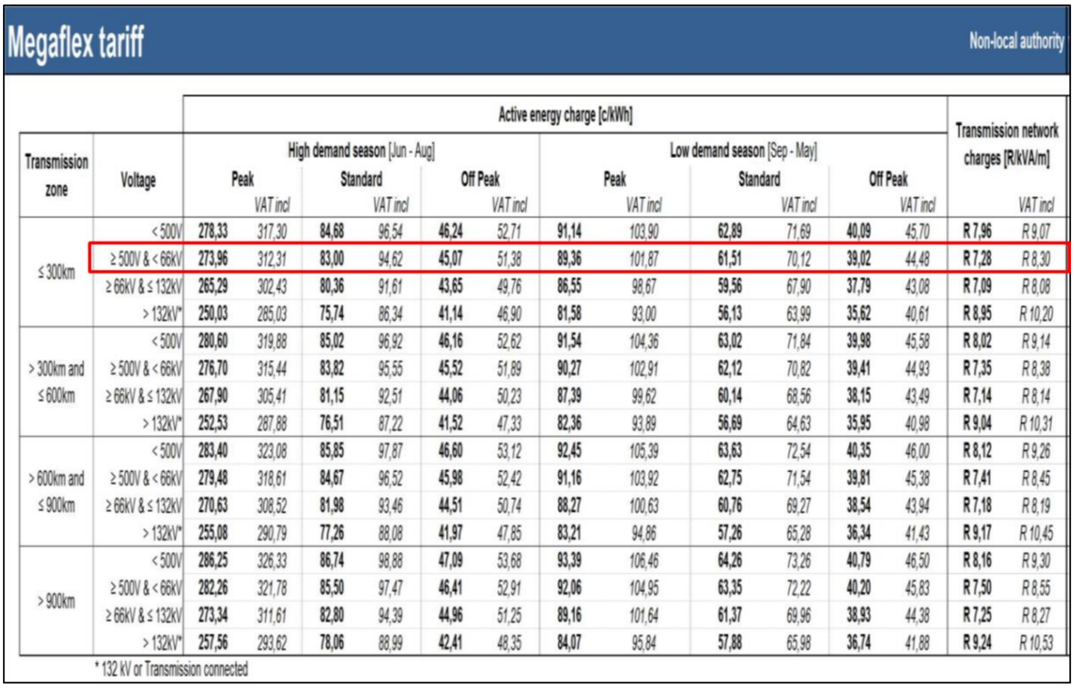
In 2007, South Africa's Department of Trade and Industry (DTI) launched its National Industrial Policy Framework. This was not a white paper document but, instead, a founding document of what would be subsequent iterations known as Industrial Policy Action Plans (IPAP). These IPAPs, which are released approximately every two years, parcel out specific issues that will be the key focus of the DTI for that period. The South African IPAP of 2016 (IPAP 2016/17-2018/19) has stated that one of the focuses of the action plan will be on overcoming constraints on the efforts that will be directed toward stabilising electricity supply constraints and supporting the development of fuel cell technology (Department of Trade and Industry, 2016a).

2.4. Electricity use in Mining

Mponeng and Mine Waste Solutions’ main electricity supply is from Eskom, which is an electricity public utility, although a minimal amount of power is self-generated with the use of hydro-turbines. There has also been research carried out in the feasibility of photovoltaic (solar power) cells for the Mponeng operation.

The Watt (W) is the standard unit of electrical power (Owlcation, 2017) and for the purposes of scale; kilowatts (kW) will be referred to. Electrical energy consumption is the rate of power use, measured in kilowatt-hours (kWh). It is determined by calculating the product of the demand of the appliance or equipment used (kW) and the amount of time that the appliance was used for (hours) (Origin Energy, 2017). In the context of mining, a third measurement is also commonly used, referred to as energy intensity, which is the amount of energy used per tonne of broken ore produced (kWh/t). Two more measures related to electrical energy are current and voltage. The former is a measure for the rate of flow of electricity as an electric current, and its standard unit is Amps (A); and the latter is the potential difference which causes an electric current to flow, measured in Volts (V) (Owlcation, 2017). The electrical energy that the provider (Eskom) sends to the operations considers the current flowing from the source to the location where it is delivered, as well as the potential difference at which that electrical energy is delivered. It is measured in kilovolt-amps (kVA) and, consequently, bills its customers based on this. This measure of kVA can, thus, be understood as the overall power delivered to the circuit (Energy Tariff Experts LLC, 2017).

The mining industry uses different types of tariff structures from Eskom, depending on the type and amount of electricity usage of a company’s operations. In the case of Mponeng and Mine Waste Solutions, the tariff on which billing is carried out is known as the Megaflex tariff (Figure 2.7). This tariff is a time of use (TOU) electricity tariff. A TOU tariff means that the time of use of electricity determines the cost of the electricity (contrast to domestic electricity use, for example, which has a constant billing rate despite the time at which the electricity is used).



Megaflex tariff

Non-local authority

Transmission zone	Voltage	Active energy charge [c/kWh]												Transmission network charges [R/kVA/m]	
		High demand season [Jun - Aug]						Low demand season [Sep - May]							
		Peak		Standard		Off Peak		Peak		Standard		Off Peak			
			VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl
≤ 300km	< 500V	**278,33**	317,30	**84,68**	96,54	**46,24**	52,71	**91,14**	103,90	**62,89**	71,69	**40,09**	45,70	**R 7,96**	R 9,07
	≥ 500V & < 66kV	**273,96**	312,31	**83,00**	94,62	**45,07**	51,38	**89,36**	101,87	**61,51**	70,12	**39,02**	44,48	**R 7,28**	R 8,30
	≥ 66kV & ≤ 132kV	**265,29**	302,43	**80,36**	91,61	**43,65**	49,76	**86,55**	98,67	**59,56**	67,90	**37,79**	43,08	**R 7,09**	R 8,08
	> 132kV*	**250,03**	285,03	**75,74**	86,34	**41,14**	46,90	**81,58**	93,00	**56,13**	63,99	**35,62**	40,61	**R 8,95**	R 10,20
> 300km and ≤ 600km	< 500V	**280,60**	319,88	**85,02**	96,92	**46,16**	52,62	**91,54**	104,36	**63,02**	71,84	**39,98**	45,58	**R 8,02**	R 9,14
	≥ 500V & < 66kV	**276,70**	315,44	**83,82**	95,55	**45,52**	51,89	**90,27**	102,91	**62,12**	70,82	**39,41**	44,93	**R 7,35**	R 8,38
	≥ 66kV & ≤ 132kV	**267,90**	305,41	**81,15**	92,51	**44,06**	50,23	**87,39**	99,62	**60,14**	68,56	**38,15**	43,49	**R 7,14**	R 8,14
	> 132kV*	**252,53**	287,88	**76,51**	87,22	**41,52**	47,33	**82,36**	93,89	**56,69**	64,63	**35,95**	40,98	**R 9,04**	R 10,31
> 600km and ≤ 900km	< 500V	**283,40**	323,08	**85,85**	97,87	**46,60**	53,12	**92,45**	105,39	**63,63**	72,54	**40,35**	46,00	**R 8,12**	R 9,26
	≥ 500V & < 66kV	**279,48**	318,61	**84,67**	96,52	**45,98**	52,42	**91,16**	103,92	**62,75**	71,54	**39,81**	45,38	**R 7,41**	R 8,45
	≥ 66kV & ≤ 132kV	**270,63**	308,52	**81,98**	93,46	**44,51**	50,74	**88,27**	100,63	**60,76**	69,27	**38,54**	43,94	**R 7,18**	R 8,19
	> 132kV*	**255,08**	290,79	**77,26**	88,08	**41,97**	47,85	**83,21**	94,86	**57,26**	65,28	**36,34**	41,43	**R 9,17**	R 10,45
> 900km	< 500V	**286,25**	326,33	**86,74**	98,88	**47,09**	53,68	**93,39**	106,46	**64,26**	73,26	**40,79**	46,50	**R 8,16**	R 9,30
	≥ 500V & < 66kV	**282,26**	321,78	**85,50**	97,47	**46,41**	52,91	**92,06**	104,95	**63,35**	72,22	**40,20**	45,83	**R 7,50**	R 8,55
	≥ 66kV & ≤ 132kV	**273,34**	311,61	**82,80**	94,39	**44,96**	51,25	**89,16**	101,64	**61,37**	69,96	**38,93**	44,38	**R 7,25**	R 8,27
	> 132kV*	**257,56**	293,62	**78,06**	88,99	**42,41**	48,35	**84,07**	95,84	**57,88**	65,98	**36,74**	41,88	**R 9,24**	R 10,53

* 132 kV or Transmission connected

Figure 2.7: Active energy charge rates for Megaflex tariff (cents per kilowatt-hours). Modified from Eskom, 2017c)

Peak, standard and off-peak time periods categorise the time of use, and this is also influenced by high and low season demands (Figure 2.8). On this tariff, bulk users are charged higher rates during peak usage hours. AngloGold Ashanti is considered to be a bulk user. The Megaflex tariff also groups customers with a notified maximum demand (NMD) greater than 1 MVA (Eskom, 2017c).

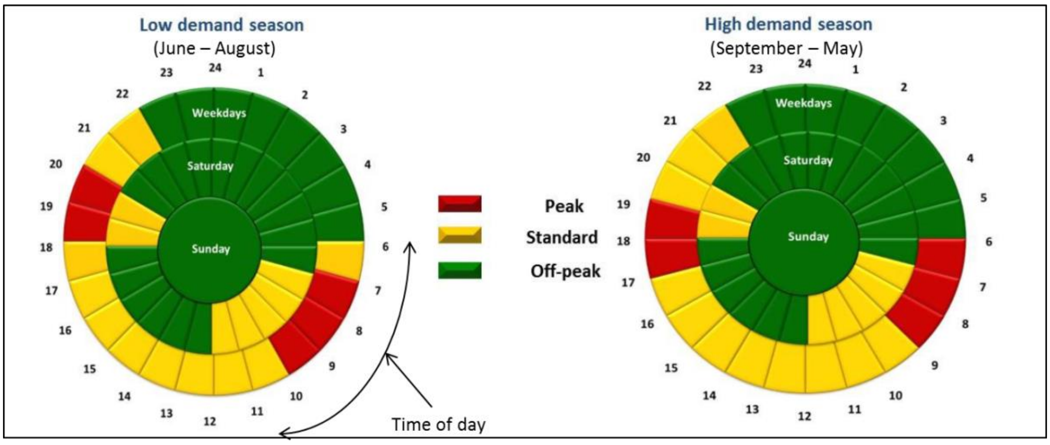


Figure 2.8: Time of use categories for low and high demand seasons (Modified from Eskom, 2017c)

The transmission zone is the geographic differentiation on which transmission network charges are levied for the delivery and transmission of electrical energy (Eskom, 2017c) and the transmission zone influences the electricity rates that are charged. AngloGold Ashanti’s operations fall within the transmission zone of less than 300km and are, therefore, charged according to this category (Figure 2.9).

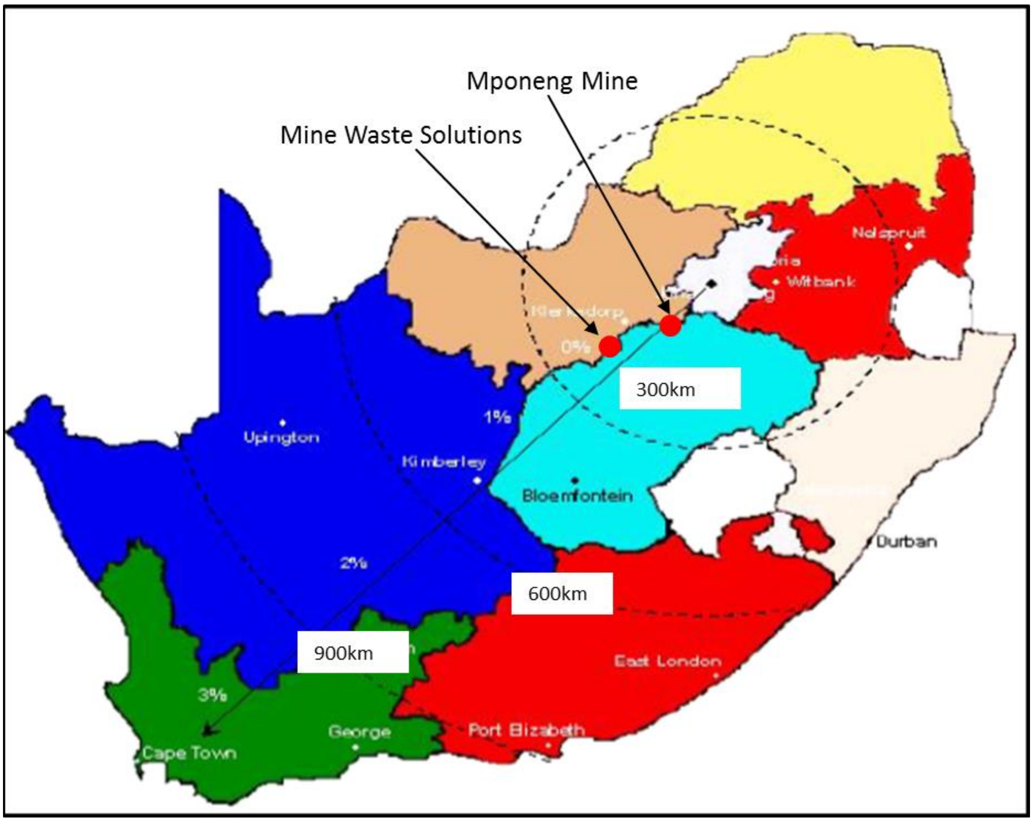


Figure 2.9: Transmission zones upon which Eskom rates are based (Modified from Eskom, 2017c)

Mining processes are isolated as much as possible so that each process and its associated electricity usage can be tracked and monitored. Electrical metering devices are placed at each of the processes for this purpose.

The implications of electricity use in the mining industry are that electricity costs constitute a significant portion of operating costs (in most cases, the cost burden is the second highest, following labour). Therefore, electricity costs can escalate significantly above what is planned and budgeted for; and this has the potential to render a mining operation less economically feasible than it was originally planned. A deep level underground gold mine such as Mponeng Mine chiefly makes use of electricity for hoisting of labour and ore, refrigeration and fans for cooling, pumping and compressed air, and, to a lesser degree, office use on surface. Mine Waste Solutions' electricity uses primarily include pumping and ore processing activities, also with a small amount of office use.

2.5. Fuel Cell Applications in Mining

The application of fuel cell technology specifically to underground mines made advances in the first decade of the new millennium, with some of the initial uses being carried out in Canada in 2002 with the use of fuel cell powered vehicles for underground use (Figure 2.10).

Figure 2.10: Fuel cell locomotive used in an underground gold mine in 2002 (Miller, et al., 2012)

This endeavour was spurred by the need to reduce greenhouse gas emissions through minimizing the use of diesel engines and in response to more rigorous health and safety regulations and increased operation depths (Sage and Betournay, 2003). The use of fuel cells was deemed more attractive due to significantly lower emissions associated with their use, and their low operating and maintenance cost (which further lowered production costs); despite their significantly high capital costs. Mining operations taking place at depths of approximately 3000m in the Sudbury Basin in Ontario, Canada, necessitated the need to devise means with which to minimize ventilation costs, which account for roughly 40% of mining operating costs. Fuel cell vehicles were identified as a solution because of their very little heat and vapour emissions, significantly lowering underground ventilation costs (Sage and Betournay, 2003). Miller (2000) acknowledged that the relatively low market price of metals and coal and production of power in underground mines resulted in economic stress for the industry; whereby prices were forced downwards and costs upwards. Thus, the cost saving that is seen with solving the problems that necessitate underground fuel cell vehicles often offsets its high capital costs, meaning that their market success is based on economic merit (Miller, 2000). Other advantages that come with fuel cell power sources over their diesel counterparts include their ease of maintenance, due to lack of moving parts, higher reliability, as well as their higher energy conversion efficiencies. Challenges include the storage and handling of hydrogen gas, which is an input of the energy generation of the fuel cell (Sage and Betournay, 2003).

The application of fuel cell technology in South Africa is relatively novel. In 2014, proof of concept trial prototypes of fuel cell locomotives at one of Anglo American Platinum Limited's (Amplats') mines in Rustenburg were carried out jointly by Amplats, Vehicle Project Incorporated of the United States of America (USA), Battery Electric and Trident South Africa (Valicek and Fourie, 2014). The purpose was to ascertain the dependability and cost-effectiveness, as well as the feasibility of fuel cell techniques for underground mining uses. Valicek and Fourie (2014) also highlighted the effects that an adoption of fuel cell powered underground mining vehicles will have for increased platinum demand and this prospective benefit was also an objective of the proof of concept trials which were carried out. The type of fuel cell used in these prototypes was the PEM form, which has been noted for its high power density, strength, technical development and positive track record. The indication from the trial was that the application of fuel cell technology for underground mining would be technically feasible, with the largest challenge being the refueling of hydrogen.

A 100kW platinum-based hydrogen fuel cell which was installed in 2015 currently provides baseload power to the Chamber of Mines (COM) building in Johannesburg (Chamber of Mines, 2016). Other similar applications in South Africa include those by Amplats. Through a successful field trial, Amplats provided power with the use of a platinum-based fuel cell to thirty four homes near Kroonstad in the Free State Province from August 2014 until the mini-grid system was decommissioned in December 2016 (Anglo American Limited, 2017). Impala Platinum Limited's (Implats') intention to take its refinery in Springs off the national grid (Donnelly, 2015) is another application. Implats is at the advanced development phase of installing an 8MW fuel cell at its refinery (Robertson, 2017). Implats' 8MW fuel cell was acquired with a twenty-year power purchase agreement; and it is over this period that the energy costs will be saved and the cost benefits of the capital will be recovered (Becker, 2017).

2.6. Fuel Cell Markets

Several analysts are anticipating an increase in the value of the fuel cell market in the years to come. According to Grand View Research (2017), the global fuel cell market size in 2015 was valued at 3.21 billion United States Dollars (USD) (Figure 2.11). In 2015, the number of fuel cells that were shipped globally exceeded sixty thousand, which totalled more than 300MW of power (Figure 2.12) (Curtain and Gangi, 2015).

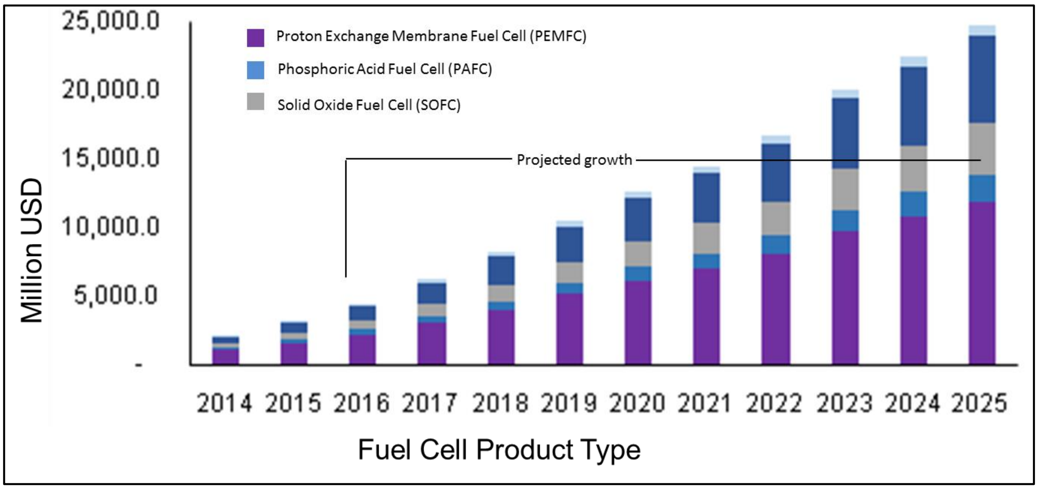


Figure 2.11: Global fuel cell market size in 2015 and forecast (Modified from Grand View Research, 2017)

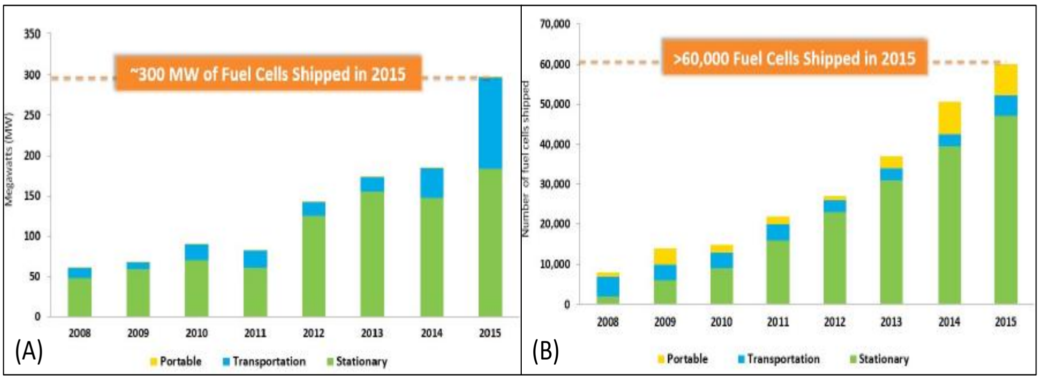


Figure 2.12: Megawatts (A) and quantity (B) of Fuel Cells Shipped Globally by Application (Modified from Curtain and Gangi, 2015)

Markets and Markets (2017) projected that the market will be worth USD5.2 billion by 2019 with a compound annual growth rate (CAGR) of 14.7% from 2014 to 2019 and Technavio (2017) predicted a CAGR of almost 23% in terms of megawatt shipments. Research and Markets (2017) forecast a CAGR of 15.4% over the next eight years to reach USD12.5 billion by 2025 while Allied Market Research (2017) estimated that the market size would grow at a CAGR of 17.36% from 2016 to 2022 to be worth USD8.64 billion by 2022. However, despite the thriving fuel cell market, a significant number of fuel cell manufacturers such as FuelCell Energy Incorporated and Plug Power Incorporated have struggled to realise momentous profits, resulting in falling stock for their companies (Dalventhal, 2017). Adamson (2016) attributed this unprofitability to the fact that the companies are manufacturing in batches and need to ramp up to scale manufacturing, but this mass manufacturing would require that companies invest and raise capital, as well as increase staffing and tooling costs; all of which erode the bottom line.

The demand for hydrogen power plants, which provide the hydrogen fuel, is likely to be fuelled by encouraging government regulations, the prospects of reducing emission rates and the competency of using domestic energy sources like natural gas (Grand View Research, 2017). Efforts by governments in the USA and Europe to reduce emissions and shift technology away from mature electric grids will also spur the growth of the fuel cell market. Where hydrogen production is concerned, the global market is anticipated to reach USD152 billion by 2021 (Markets and Markets as cited by Lundin and Eriksson, 2016). Fuel cells are expected to contribute to 140 million kilograms of hydrogen demand in 2030, which will only constitute 0.56% of the global hydrogen demand from all industries (Lux Research Incorporated, 2013; Lundin and Eriksson, 2016).

Grand View Research (2017) further postulated that the cost efficiency and the economic viability of fuel cell technology will be fostered by public-private partnerships. The most common type of fuel cell, which made up more than 65% of global shipments in 2015 was the PEM fuel cell due to its practicality in a wide range of applications which include primary and backup power systems, forklifts and automobiles, amongst others. The largest application segment that is expected to be seen is the stationary power plant, which is anticipated to account for 70% of total shipments, due to its high efficiency and ability to use different fuels (Figure 2.13) (Grand View Research, 2017).

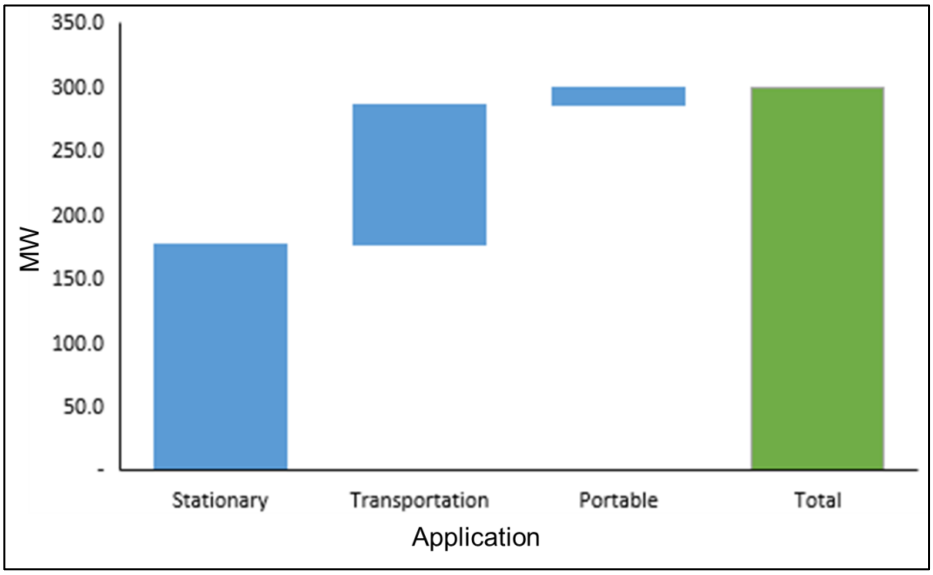


Figure 2.13: Global fuel cell market capacity by application in 2015 (Modified from Grand View Research, 2017)

Low manufacturing volume, significant labour intensity in the manufacturing process, coupled with limited manufacturing experience and the need to recover development costs mean that purchasing costs of fuel cells and the metal hydrides which provide hydrogen as a fuel are high (Miller, 2000). These high purchasing costs create a constraint for acquiring fuel cells. However; advancements in technology are likely to reduce the cost of fuel cells (Allied Market Research, 2017). Implats also expected an eventual decrease in the capital costs of fuel cells as distribution increases, noting that the capital cost has decreased by 15% to 20% over several years (Impala Platinum Limited, 2017). According to 4th Energy Wave (2015), at a cumulative installed capacity of 50MW, the PEMFC and SOFC were at a lower price point than solar and wind were at a comparable point in their development, respectively (Figure 2.14).

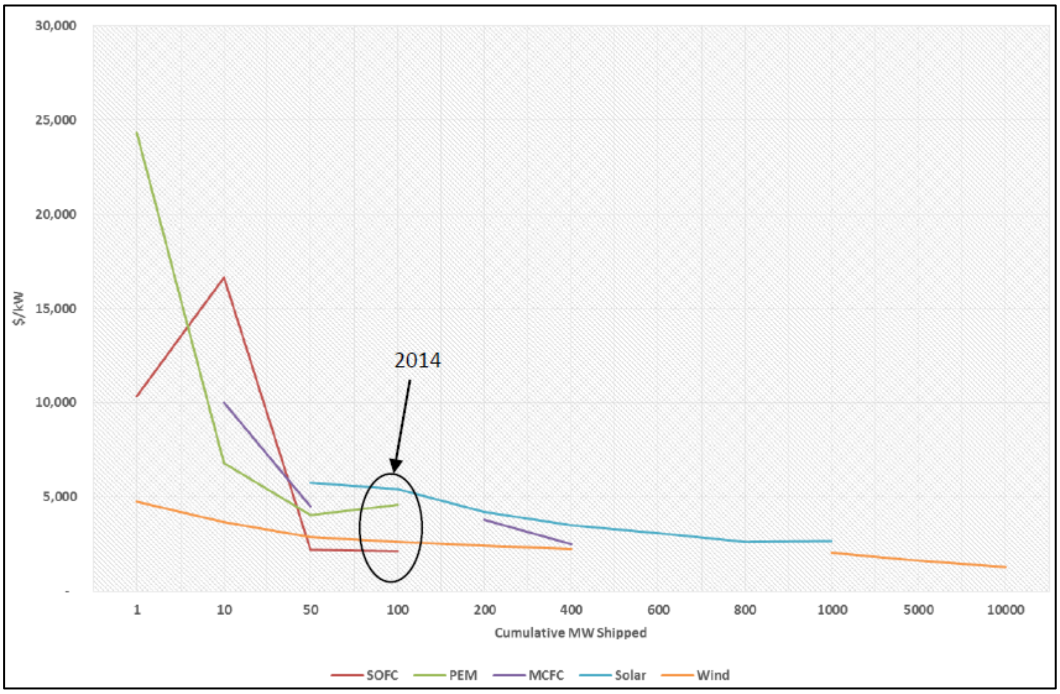


Figure 2.14: Price points for PEM, SOFC, MCFC and wind and solar over cumulative MW shipped (4th Energy Wave, 2015)

In terms of regional dominance of the fuel cell market, North America is the largest in terms of installed capacity. Approximately 50% of global installed capacity was in North America in 2015 and this is the result of the regulatory framework and technological advancements in the region. The Asia Pacific region is dominant in manufacturing (Lundin and Eriksson, 2016). It is expected that North America will remain the leading market because of the commercialisation and embracing of fuel cell technology (Grand View Research, 2017). Specific nations which are leading in their growth in the manufacture, shipment and adoption of fuel cell technology include Germany, Japan, South Korea and China (Figure 2.15) (4th Energy Wave, 2015).

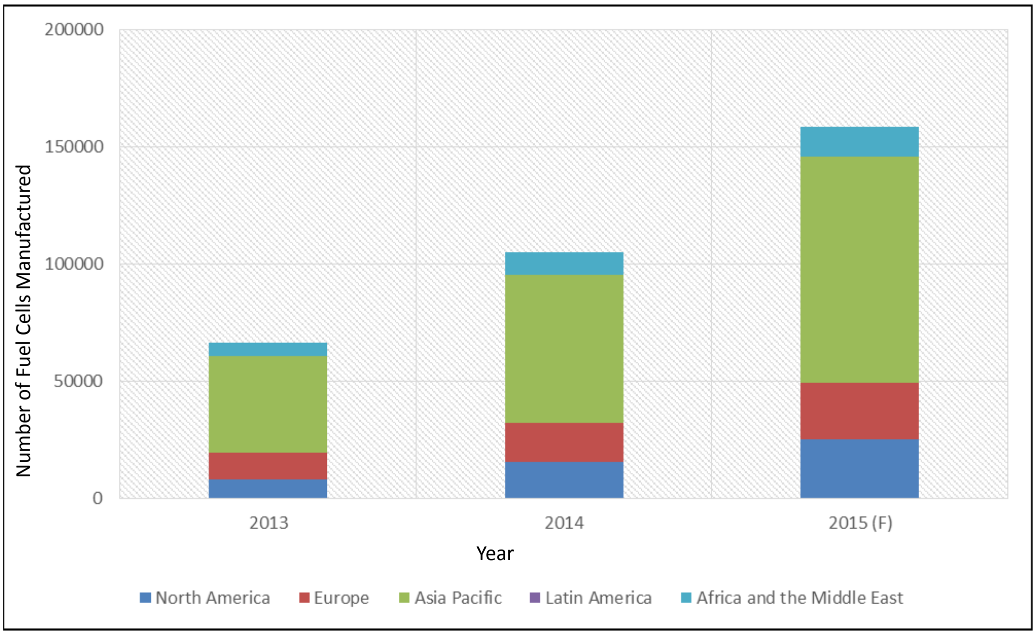


Figure 2.15: Global break-down of fuel cell manufacture regions (4th Energy Wave, 2015)

The global fuel cell market is considered to be highly fragmented, with several small and medium enterprises and sizeable fuel cell companies worldwide (Technavio, 2017), creating a highly competitive environment. In 2015, 4th Energy Wave (2015) observed the nations which directly and indirectly had policies conducive to the advancement of fuel cells (Figure 2.16). It was noted in their review that South Africa displayed potential and had put in place robust strategies to attain further advancements. These advancements are likely the result of efforts from Implats, Amplats and COM as already noted.

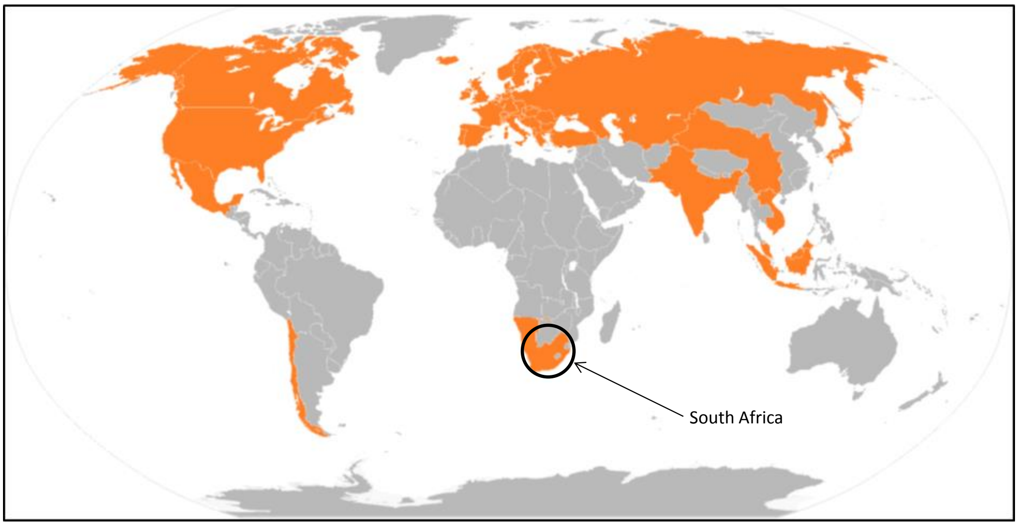


Figure 2.16: Countries where fuel cells are directly or indirectly supported by policy (4th Energy Wave, 2015)

Currently, there are no fuel cell manufacturers or vendors in South Africa. Nonetheless, Isondo Precious Metals (IPM), significantly supported by the DTI, commenced the construction of a fuel cell plant in the OR Tambo Special Economic Zone (SEZ). This plant was expected to be operational in the third quarter of 2017, and it was anticipated to spur the localisation of fuel cell component fabrication as well as platinum beneficiation in line with government objectives (Department of Trade and Industry of South Africa, 2017d). Furthermore, this manufacturer of core components will serve to help overcome the cost barrier which has suppressed demand for fuel cell technology (Fuel Cells Bulletin, 2017). These fuel cell components will join the global supply chain and South Africa’s relatively lower manufacturing costs will make local manufacturing more competitive (Creamer, 2017a). The potential benefit that this component manufacturer will have on South African fuel cell installations is the local access to components when needed. IPM has intentions to advance its manufacturing into the fabrication of complete fuel cell stacks and systems (Khan, 2017). A report by 4th Energy Wave (2015) noted that South Africa made a number of significant advances in fuel cell markets which were driven largely by industry and expects that, in the short to medium term, it could become one of the top five nations in terms of installed capacity.

The leading fuel cell manufacturers in the market were identified by Technavio (2017) as Ballard Power Systems, Bloom Energy, Nuvera Fuel Cells and SFC Energy. Market opportunities for fuel cell technology exist not only for the manufacturing and assembly of components, but also for supporting market sectors such as hydrogen production and refueling station technologies (Lundin and Eriksson, 2016).

2.7. Conclusion

Fuel cells are more favourable than conventional methods of generating power such as diesel and coal, largely due to their energy efficiency and reduced emissions. A review of market analyses points to a growing global fuel cell market which is expected to grow at double-digit growth rates over the next several years, indicating that there are encouraging prospects for increased applications in fuel cells. These prospects stand to have positive implications for the beneficiation of South African platinum. The capital costs of fuel cells are high; however, technological advances are likely to reduce these high costs of purchase. The next chapter will delve into the advancements that have been made in fuel cell technology across the globe; detailing the efforts that a number of nations have made to support the growth of the technology.

3. The Global Development and Adoption of Fuel Cell Technology

3.1. Introduction

The workings of fuel cells have been demonstrated since the 1830s, a time during which the internal combustion engine was far more popular (Jackson, 2016). However, it has not been until fairly recently that they have gained popularity for energy generation. The lag in the time that it has taken for the technology to develop has been centred largely on research and development aimed at making the development and capital costs of acquisition more economically viable. Lundin and Eriksson (2016) cited less investment into fuel cell technology as compared to batteries and combustion engines as a reason for the former's sluggish development. The rapidly increasing adoption of fuel cell technology has been assisted by the global shift towards cleaner energy and the commitment made by many nations to reduce greenhouse gas emissions, which have been responsible for climate change.

New Energy World (2011) identified Japan and the USA as world leaders in the advancement of fuel cell technology in terms of deployment and the material handling vehicles sector, respectively. Following these nations is Europe, with South Korea and China making quick strides in development. By 2010, these regions had collectively invested over USD1 billion in fuel cell and hydrogen technology (Figure 3.1). The forces for fuel cell technology and hydrogen development are unique in each region, with the USA being motivated largely by energy surety, air quality, wealth creation and industrial development. Japan and the European Union (EU) are driven primarily by environmental goals, industrial competitiveness and energy security (New Energy World, 2011).

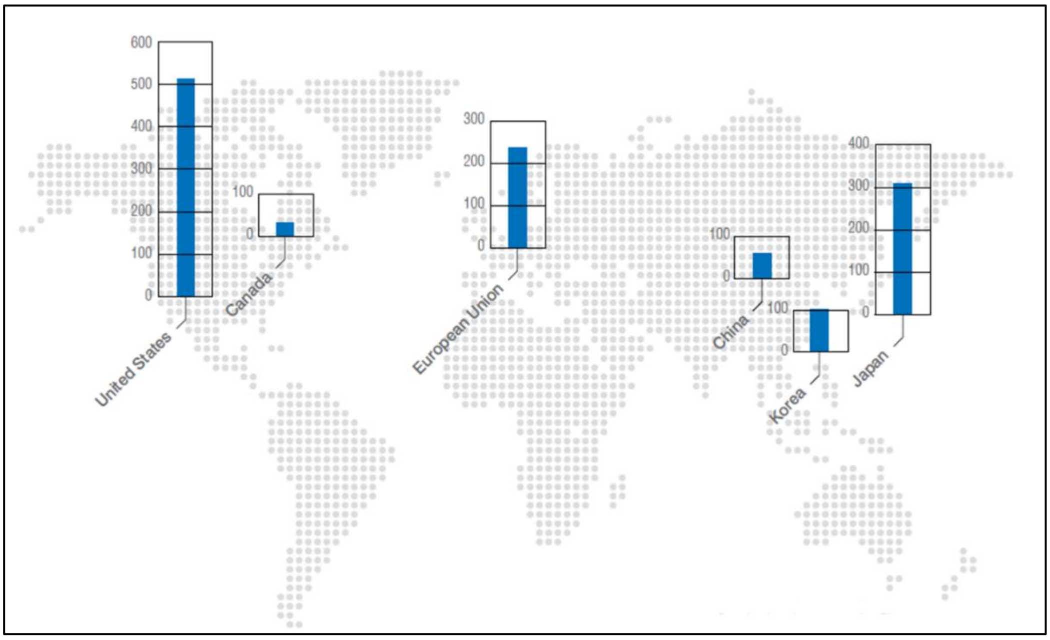


Figure 3.1: Global investment (million USD) in fuel cell and hydrogen technology up to 2010 (New Energy World, 2011)

Regions where developments in fuel cell and hydrogen technology are relatively novel, such as India and Africa, were brought up by New Energy World (2011) as possessing potential to become growth markets for future decades. For example, India's growing economy and large population, which need energy security and supply to support their growth, and Africa's large telecommunications market and inadequate power system are some of the supporting reasons.

This chapter will detail the efforts that various regions such as North America, Europe, Asia and Africa have made, which allowed for them to become world leaders in the advancement of this technology. These efforts have been mostly through policy interventions as well as private-public collaborations. These interventions and endeavours will be grouped into regions. It is important to gather understanding on what other regions have done to support the growth of fuel cell technology, either through manufacturing, adoption or both. This will assist in identifying the capabilities that need to be developed in South

Africa for similar advances to be made. Although Africa is not at the same stage of advancement and adoption as the other three regions, the developments that have been made in this region will be noted. Attention will be particularly on South Africa, so that a current standing can be appreciated.

3.2. Global Trends in Fuel Cell Technology

3.2.1. North America

The USA, which has managed to develop and cultivate its fuel cell industry, has been able to do so because of active government support. There have also been increased efforts to strengthen its skills base through teaching programmes and the wide-scale dissemination of learning material. The USA government plays a significant role in funding research and development in hydrogen and fuel cell technology, following behind the Japanese and South Korean governments (4th Energy Wave, 2015). In 2010 and 2011, the United States Department of Energy (USDOE) had allocated USD170 million for fuel cell research and development, demonstration and commercialisation endeavours (New Energy World, 2011). The USDOE established a division for fuel cell technology known as the Fuel Cell Technologies Office (FCTO) which carries out research and development in order to surmount economic, technological and institutional barriers to the development of fuel cells and hydrogen. The FCTO also supports manufacturing research and development to advance manufacturing processes and reduce the cost of constituents and systems (Fuel Cell Technologies Office, 2017a). Federal agencies in the USA are adopting fuel cell technology within their facilities, and this federal action assists in leading by example and contributes to the economy through the acquisition of fuel cells (Fuel Cell Technologies Office, 2017b). Through this acquisition, it becomes possible to attain the economies of scale required to bring the price point of fuel cells down and to create a local fabrication and supplier foundation. This foundation creates numerous employment opportunities within the fuel cell industry, thereby attaining the market transformation that the FCTO aims to achieve through its research and development (Fuel Cell Technologies Office, 2017b). The deployment of fuel cell technology in the USA has been heavily reliant on fiscal subsidy (4th Energy Wave, 2015), with several states exercising financial incentives to aid the setting up of hydrogen and fuel cell stations (New Energy World, 2011). There is a challenge in making fuel cells economically viable. However, fuel cell development supported by the USDOE has resulted in fuel cells achieving market competitiveness by increasing their durability and reducing the amount of platinum required (United States Department of Energy, 2014).

Additional support for the advancement of the technology also came from a staunch environmental perspective as there was an increased mandate to reduce carbon emissions and develop alternative energy sources. The regulatory framework in California supported the push for hydrogen infrastructure. In 2013, a bill was signed into law which requires the state of California to report on the availability of hydrogen fueling stations so that locations needing further investment can be determined. Furthermore, a large portion of the hydrogen fueling stations are co-funded by the state (Swigonski, 2016). Dalventhal (2017) expected a Trump presidency to dampen the advances that have been made by United States' fuel cell companies, as the president has stated skepticism over climate change.

Cavendish Energy LLC (2016) compiled a list of core occupations and the associated minimum academic qualifications that will be required by a growing fuel cell industry. In the USA, where fuel cell technology and the hydrogen sector are growing, opportunities for new employment have been identified (Table 3.1).

Table 3.1: Core occupations and associated qualification requirements in the fuel cell industry (Modified from Cavendish Energy LLC, 2016)

Occupation	**Minimum Qualification Requirement**
Director of hydrogen energy development	Bachelor's (Business) degree
Hydrogen/fuel cell R&D director	Doctorate
Hydrogen fuel cell system technician	High School Qualification/On the Job Training/Trade School/Apprenticeship
Junior hydrogen energy technician	High School Qualification/On the Job Training/Trade School/Apprenticeship
Fuel cell engineering intern	High School Qualification/On the Job Training/Apprenticeship
Fuel cell manufacturing technician	Associate certificate
Fuel cell fabrication and testing technician	Associate certificate
Hydrogen power plant installation, operations, engineering and management	Bachelor's (Electrical, Mechanical, Chemical) Engineering degree
Hydrogen energy systems designer	Apprenticeship/Trade School
Fuel cell plant manager	Bachelor's (Electrical, Mechanical) Engineering degree
Hydrogen energy system operations engineer	High School Qualification
Hydrogen fueling station designer & project engineer	Bachelor's Engineering degree
Hydrogen fuel transporter – trucker	On the Job Training
Hydrogen fueling station operator	On the Job Training
Hydrogen fuels policy analyst & business sales	Bachelor's (Business) degree

Hydrogen systems program manager	Bachelor's Engineering degree
Emissions accounting & reporting consultant	Bachelor's (various) degree
Fuel cell quality control manager	Master's (Science/Engineering) degree
Hydrogen pipeline construction worker	High School Qualification/On the Job Training/Trade School/Apprenticeship
Fuel cell designer	Master's (Science) degree
Hydrogen energy engineer	Bachelor's Engineering degree
Fuel cell power systems engineer	Master's (Electrical) Engineering degree
Fuel cell fabrication technician	High School Qualification/On the Job Training/Trade School/Apprenticeship
Hydrogen systems & retrofit designer	Bachelor's degree
Fuel cell retrofit installer	High School Qualification/On the Job Training/Trade School/Apprenticeship
Fuel cell retrofit manufacturer plant labor	High School Qualification
Hydrogen vehicle electrician	High School Qualification/On the Job Training/Trade School/Apprenticeship
Fuel cell vehicle development engineer	Bachelor's Engineering degree
Hydrogen systems safety investigator - cause analyst	Bachelor's (various) degree
Hydrogen lab technician	Associate certificate
Hydrogen energy system installer helper	High School Qualification
Hazardous materials management specialist	Bachelor's (Science) degree
Hydrogen energy system installer	High School Qualification/On the Job

	Training/Trade School/Apprenticeship
Fuel cell power systems operator and instructor	High School Qualification/On the Job Training/Trade School/Apprenticeship
Fuel cell backup power system technician	High School Qualification/On the Job Training/Trade School/Apprenticeship
Senior automotive fuel cell power electronics engineer	Bachelor's (Electrical) Engineering degree
Emissions reduction credit portfolio manager	Bachelor's (Business) degree
Emissions reduction project developer specialist	Bachelor's (various) degree
Emissions reduction project manager	Bachelor's (various) degree
Hydrogen systems sales consultant	Bachelor's (Business) degree
Hydrogen plant operations manager	Bachelor's (Electrical, Mechanical) Engineering degree

The United States Department of Energy (2014) also lists similar occupations and skills requirements, highlighting the necessity for the science and engineering backgrounds linked to product and technology development required for the majority of the employment opportunities. Career opportunities exist for mechanical, chemical, industrial and electrical engineers, material scientists, laboratory, vehicle and hydrogen production technicians, factory workers, power plant operators and maintenance staff, amongst others.

Cavendish Energy LLC (2016) conceded that a large portion of these occupations will require a different skillset than occupations which exist currently, with requirements for training which will ensure a sufficient supply of trained professionals in the labour market. The USDOE has employed an approach whereby training is provided to inexpert instructors from experienced facilitators, and the inexperienced are guided in developing the necessary skills they require in order to impart knowledge themselves (United States Department of Energy, 2014). The FCTO has worked to advance curricula aimed at improving the skills associated with the fuel cell industry, through specialized courses, teaching materials, demonstrations and programmes (United States Department of Energy, 2014).

Argonne National Laboratory (ANL) and RCF Economic and Financial Consulting Incorporated have gone as far as to develop a spreadsheet model which determines the economic impact of fuel cell deployment for various applications and markets of fuel cells. This model is known as the Jobs and Output Benefits of Stationary Fuel Cells (JOBS FC) and it was developed for the USDOE’s FCTO (Mintz, 2012). The model can be used by numerous bodies which include companies, government agencies and development corporations. The user inputs different assumptions such as fuel cell size, the target number of fuel cells to be produced, fuel cell application and market. From this, the number of direct and indirect jobs and associated wages and sales figures will be determined from the input assumptions (Mintz, 2012). Additional inputs required for the basic estimation are the geographic location of the manufacturing, the number of units to be produced annually and whether the operation under consideration is an expansion of an existing facility or a new construction (Figure 3.2).

* * * PEM MANUFACTURING FACILITY CONSTRUCTION/EXPANSION MODULE * * *

REQUIRED USER INPUT FIELDS

Step 1 - Choose Region

Select State or Region	<Please select>

Step 2 - Manufacturing Facility Construction or Expansion

Will this be a New production facility or will an existing production facility be Expanded?

Choose Option	<Please select>

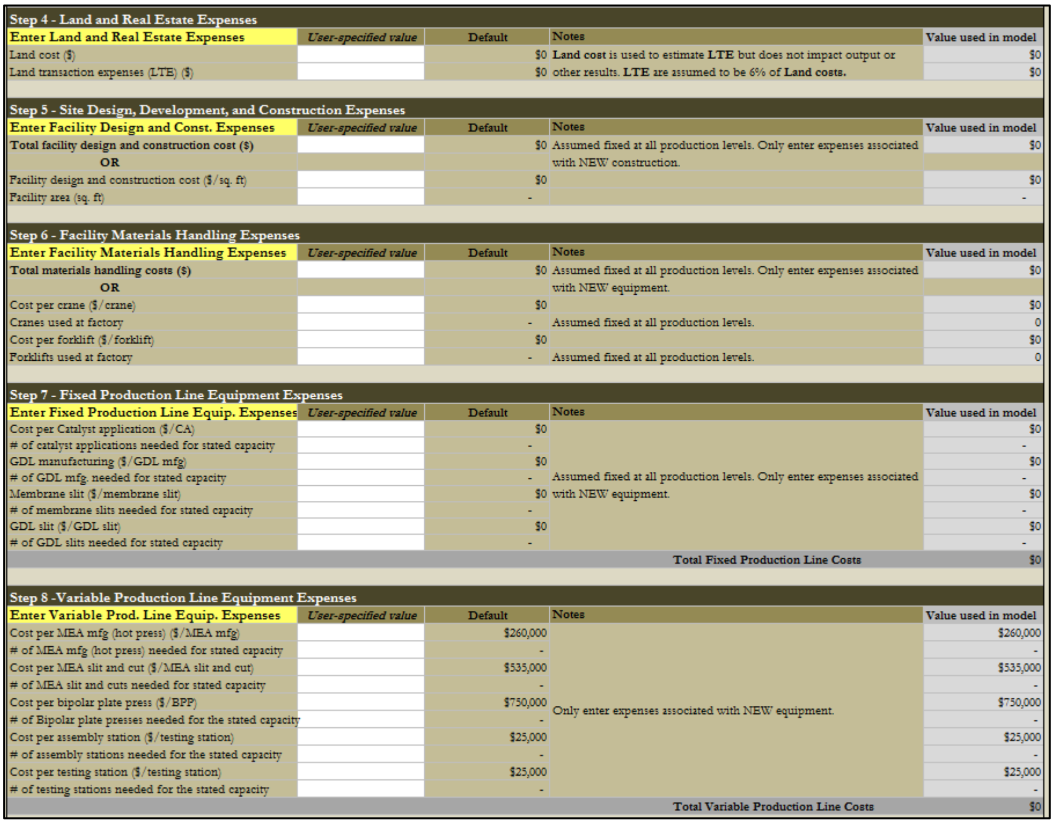
Step 3 - Annual Manufacturing Capacity

What is the maximum number of PEM units that the new facility will be able to produce annually?

Step 3a - Enter Needed Annual Capacity	*User-specified value*	Notes	Value used in model
Needed annual production (number of 5 kW BuP unit equivalents)		Capital capacity requirements are based off of a 5 kW PEM backup power fuel manufacturing facility as outlined in Battelle (2011). Values should be entered in 5 kW BuP unit equivalents.	-
Step 3b - Enter Current Annual Capacity	*User-specified value*	Notes	Value used in model
Current annual production (number of 5 kW BuP unit equivalents)		Capital capacity requirements are based off of a 5 kW PEM backup power fuel manufacturing facility as outlined in Battelle (2011). Values should be entered in 5 kW BuP unit equivalents.	-

Figure 3.2: Input parameters required for PEM manufacturing facility (Mintz, 2012)

Optional additional inputs can also be made, which go into the intricacies of the facility. Such details include land expenses, design and construction expenses, facility materials handling expenses, and fixed and variable production line equipment expenses (Figure 3.3).



Step 4 - Land and Real Estate Expenses

Enter Land and Real Estate Expenses	*User-specified value*	Default	Notes	Value used in model
Land cost ($)		$0	**Land cost** is used to estimate **LTE** but does not impact output or other results. **LTE** are assumed to be 6% of **Land costs.**	$0
Land transaction expenses (LTE) ($)		$0		$0

Step 5 - Site Design, Development, and Construction Expenses

Enter Facility Design and Const. Expenses	*User-specified value*	Default	Notes	Value used in model
Total facility design and construction cost ($)		$0	Assumed fixed at all production levels. Only enter expenses associated with NEW construction.	$0
OR				
Facility design and construction cost ($/sq. ft)		$0		$0
Facility area (sq. ft)		-		-

Step 6 - Facility Materials Handling Expenses

Enter Facility Materials Handling Expenses	*User-specified value*	Default	Notes	Value used in model
Total materials handling costs ($)		$0	Assumed fixed at all production levels. Only enter expenses associated with NEW equipment.	$0
OR				
Cost per crane ($/crane)		$0		$0
Cranes used at factory		-	Assumed fixed at all production levels.	0
Cost per forklift ($/forklift)		$0		$0
Forklifts used at factory		-	Assumed fixed at all production levels.	0

Step 7 - Fixed Production Line Equipment Expenses

Enter Fixed Production Line Equip. Expenses	*User-specified value*	Default	Notes	Value used in model
Cost per Catalyst application ($/CA)		$0	Assumed fixed at all production levels. Only enter expenses associated with NEW equipment.	$0
# of catalyst applications needed for stated capacity		-		-
GDL manufacturing ($/GDL mfg)		$0		$0
# of GDL mfg. needed for stated capacity		-		-
Membrane slit ($/membrane slit)		$0		$0
# of membrane slits needed for stated capacity		-		-
GDL slit ($/GDL slit)		$0		$0
# of GDL slits needed for stated capacity		-		-
			Total Fixed Production Line Costs	$0

Step 8 -Variable Production Line Equipment Expenses

Enter Variable Prod. Line Equip. Expenses	*User-specified value*	Default	Notes	Value used in model
Cost per MEA mfg (hot press) ($/MEA mfg)		$260,000	Only enter expenses associated with NEW equipment.	$260,000
# of MEA mfg (hot press) needed for stated capacity		-		-
Cost per MEA slit and cut ($/MEA slit and cut)		$535,000		$535,000
# of MEA slit and cuts needed for stated capacity		-		-
Cost per bipolar plate press ($/BPP)		$750,000		$750,000
# of Bipolar plate presses needed for the stated capacity		-		-
Cost per assembly station ($/testing station)		$25,000		$25,000
# of assembly stations needed for the stated capacity		-		-
Cost per testing station ($/testing station)		$25,000		$25,000
# of testing stations needed for the stated capacity		-		-
			Total Variable Production Line Costs	$0

Figure 3.3: Additional input parameters required for PEM manufacturing facility (Mintz, 2012)

3.2.2. Europe

In Europe, the United Kingdom (UK) has pledged to reduce its greenhouse gas emissions by 80% by 2050 (Le Page, 2016). Additionally, an intention to ban the sale of new diesel and petrol cars by 2040 in order to encourage the widespread use of electric and hybrid vehicles has been announced (Swinford, 2017). These goals may create a market opportunity for fuel cell vehicles for the UK. Vehicles driven by hydrogen have a better driving range than electric cars and do not have downtime associated with their recharging, compared to zero-emission vehicles such as electric vehicles which require lengthy interruption at charging stations (Felton, 2017). Charging periods for electric vehicles can take anywhere from thirty minutes to twelve hours, depending on the battery size (Pod Point, 2017). New Energy World (2011) acknowledged that fuel cell technology will be one of the technologies looked to in Europe if the goal of a low carbon economy is going to be attained. It has been incorporated into the European energy and sustainable transport policies. Current efforts to advance the technology have been aided by research and development ventures carried out within the European Research and Development framework programme. The result has been growth in progressing the technology, particularly in the transport sector (New Energy World, 2011).

What Germany has done is to construct fueling stations in the country so that demand can be met as fuel cell vehicles are introduced. Europe, through a collaborative project between fifteen partners (termed the HyFive Project), has a goal to expand its fueling network within major cities (Swigonski, 2016). HyFive is a project which has a goal of deploying a large number of fuel cell electric vehicles from several automotive companies, which include BMW, Toyota, Honda, Hyundai and Daimler, which are spearheading commercialisation (Fuel Cells and Hydrogen, 2017). In 2008, a partnership known as the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) between the European Commission and the private sector was founded with each party funding 50% of 940 million Euros towards a research and development programme (New Energy World, 2011). The areas of focus for the FCH JU include hydrogen refueling infrastructure, sustainable hydrogen production, heat and power generation from stationary fuel cells, fuel cells for commercial utilisation and the regulations, codes and standards associated with the listed focus areas. The German government and industry have collectively invested billions of euros into funding hydrogen and fuel cell technology programmes in an effort to have an economy free of carbon dioxide by 2050. It aims to have 400 refueling stations by 2025 and 1000 stations by 2030 from the current 23 that exist in 2017 (Cloete, 2017).

The EU has been carrying out the greatest fuel cell bus demonstration in the world with a public-private partnership in Europe termed the Clean Hydrogen

In European Cities (CHIC) project (New Energy World, 2011). CHIC is a European project which is one of numerous fuel cell and hydrogen projects co-funded by FCH JU, comprising twenty-three partners from eight European nations. It is responsible for the deployment of a large fleet of fuel cell buses and the accompanying hydrogen refueling stations. Bus manufacturers, transport companies, research bodies and infrastructure suppliers are some of the parties involved in the project (Clean Hydrogen in European Cities, 2017). Deployment of the fuel cell buses has been carried out with the facilitation of the CHIC project in Switzerland, Italy, UK, Norway, Germany and Canada (Clean Hydrogen in European Cities, 2017).

What has been highlighted by New Energy World (2011) where the adoption of fuel cell technology is concerned is that a market-driven approach will not work in isolation. This is chiefly because political, social and environmental motivations are behind the shift towards cleaner energy and not market indicators. The adoption requires joint efforts by partnerships between private and public stakeholders as the primary risks and costs that come with this shift are too great for private enterprises alone. Europe is advantaged in any attempts to increase fuel cell adoption in that it has a mature hydrogen production infrastructure, possessing the largest hydrogen pipeline system in the world (New Energy World, 2011).

3.2.3. Asia

Lundin and Eriksson (2016) stated that Japan is a global leader in the adoption of small-scale fuel cells providing residential power generation and the advancement of hydrogen-fueled cars. In 2014, the Japanese government released a document known as the Promotion Project for Hydrogen Society Using Renewable Energy (4th Energy Wave, 2015). This strategic roadmap was set in a number of phases. The first phase entailed an increase in the number of residential fuel cells and hydrogen refueling stations, 5.3 million in 2030 and 100 by 2015, respectively. It also involved the commercialisation of fuel cell vehicles by 2015 and fuel cell buses by 2016. The second phase involves the extension of the domestic hydrogen network and the production, transportation and storage of hydrogen in foreign countries while the third phase aims to achieve a complete carbon-dioxide free hydrogen supply system (4th Energy Wave, 2015). The fuel cell technology and hydrogen market in Japan is, therefore, driven by their ambition to make a hydrogen society out of the nation (Lundin & Eriksson, 2016). Subsidies in Japan have been employed to introduce fuel cell vehicles and residential fuel cells (Hashimoto, 2015). This aggressive approach to supporting the development of fuel cell technology in Japan has allowed for the companies in Japan, such as Toyota, to extend their fuel cell products to the rest of the globe. In July 2014, it was stated that fuel cell cars would be rolled out as official vehicles for the Japanese ministries (4th Energy Wave, 2015). Toyota's efforts at experimenting with fuel cell vehicles have led to the development of a fuel cell-powered eighteen wheeler truck (Torchinsky, 2017). Toyota's eager determination to further shift Japan towards a hydrogen society were seen in 2015, when it stated that it would make more than 5600 of its fuel cell and hydrogen technology patents free (IflScience (2016) as cited by Lundin and Eriksson (2016)).

An effort to achieve economies of scale in Japan has also been seen, where fuel cell co-generation systems were introduced commercially for household electricity generation. Government subsidised the capital expenditure on them by 50%, resulting in the installation of more than 113 000 units by March 2015 and a reduction in the price of fuel cell systems through economies of scale (Figure 3.4) (Hashimoto, 2015).

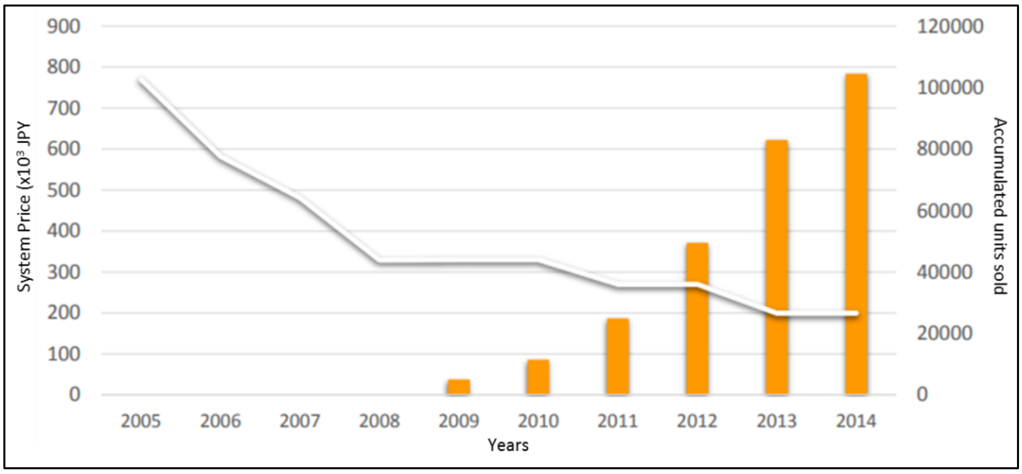


Figure 3.4: Demonstration of economies of scale in fuel cell system sales in Japan (Modified from (Hashimoto, 2015)

According to Lundin and Eriksson (2016), Japan's government estimated that adopting fuel cells into residences would create an energy saving of roughly 23%. The Japanese government also changed its energy policy after the Fukushima nuclear disaster in 2011 to include hydrogen as an important ancillary energy carrier. One of the ways in which hydrogen would be introduced into society would be through the adoption of residential and vehicular fuel cells with the construction of accompanying hydrogen refueling stations. Clear targets with their timeframes were laid out for this. The Japanese government also has the ambition of utilising fuel cell vehicles and buses at their Tokyo Olympics in 2020 (Akiba, 2017). It also intends to increase investment in research and development for environmentally friendly energy technology to approximately 90 billion Japanese Yen (JPY) by 2021 (Nikkei Asian (2016) Review as cited by Lundin and Eriksson, 2016). It currently spends 0.07% of its GDP, which equates to an approximate JPY350 billion on energy-related research and development, which is amongst the highest proportion among industrialised nations (Lundin and Eriksson, 2016).

The importance of hydrogen infrastructure was seen when the sales of Totoya's Mirai, a hydrogen fuel cell vehicle, were adversely affected by the sparse fueling infrastructure needed to support the vehicle in the USA (Felton, 2017). The Japanese automotive manufacturer has been slow in establishing enough hydrogen fueling stations at which vehicles can be refueled as the result of challenges with the local fire codes that are not provisional for hydrogen (Felton, 2017). Lundin and Eriksson (2016) have mentioned high construction costs for establishing additional refueling stations as a challenge. There is, however, a slow and steady increase in the number of stations being constructed (Felton, 2017). Several automotive manufacturers in Japan, including Honda, Nisan and Toyota, have partnered with a number of gas companies in Japan to develop a hundred-station hydrogen highway. A similar collaboration between Hyundai-Kia Motor Corporation and the South Korean government has seen a number of stations constructed in that country (Swigonski, 2016). According to Swigonski (2016), a typical hydrogen fueling station takes eighteen to thirty-six months to construct, costing around USD1 million each, meaning that construction is a feat which will take time to achieve.

South Korea stated an intention to supply 20% of the world’s fuel cell shipments and create 560 thousand jobs by 2025. This would be carried out while implementing a subsidisation program that would subsidise a significant portion of the cost of residential fuel cells which would decrease from 80% in 2010/2011 to 30% from 2017 to 2020 (New Energy World, 2011). In China, fuel cell technology has been under development since the 1970s. China has a number of commercial fuel cell companies (Fuel Cell Today, 2012), with its investment into fuel cell energy totaling USD100 billion to date (Dalventhal, 2017). As one of the highest emitters of greenhouse gases, China, which makes use of coal-fired power, has a significant opportunity to use fuel cells to attain the low carbon economy that most of the world is striving towards. Other opportunities for the growth of fuel cell technology in China exist due to the considerable domestic automobile manufacturing industry and the fact that

China has the biggest, ever-increasing network of mobile telecommunications in the world (Fuel Cell Today, 2012).

China has carried out a number of demonstration programs, particularly for the transportation sector, some of them public transportation demonstrations and others concurring with high profile occasions such as the Beijing Olympics. In 2008 fuel cell electric vehicles were used as support cars for organisers, special guests and the press for the Beijing Olympics (Fuel Cell Today, 2012). The average range of the fuel cell vehicles during the Beijing Olympics was 235km per tank of hydrogen. Thereafter, the fleet of fuel cell vehicles was sent to California for a set of demonstrations in 2009 and, in the 2010 World Expo, fuel cell cars and buses were used to transport visitors (Fuel Cell Today, 2012).

Where government participation is concerned, the Chinese government granted funds to subsidise the purchase of vehicles which were intended for public use, like buses and taxis, in 2009. Research and development for fuel cell technology and hydrogen is financed through government programmes, with progress targets and funding levels determined by the Ministry of Science and Technology (Fuel Cell Today, 2012).

3.2.4. Africa

In South Africa, there are some substantial strides that the DTI has made in terms of facilitating the necessary projects which form the groundwork for future local fuel cell manufacturing. In order to facilitate industrial and economic development, the SEZ Programme has been established by the DTI. SEZ are geographically selected areas reserved for economic undertakings and, through exclusive arrangements and support systems, they are aimed at attracting foreign and local investments and industrial capability development (Department of Trade and Industry of South Africa, 2017a). Two such zones that are relevant to local fuel cell manufacturing are Implats’ fuel cell manufacturing hub in Springs and IPM’s fuel cell components plant in the OR Tambo SEZ. ZAR15 million was provided by the DTI to IPM for the feasibility phase of the components manufacturing project and the department is also involved in progressing an industrial area for fuel cell and battery production in the zone (Department of Trade and Industry of South Africa, 2016b). IPAP 2017/18-2019/20 indicated that the DTI intends to strengthen the system of industrial finance and incentives to support increased investment in sectors such as fuel cell technology. The DTI, together with the Industrial Development Corporation of South Africa (IDC), has earmarked several fuel cell markets which include stationary, mobile and mining equipment, for further development (Department of Trade and Industry of South Africa, 2017b). The Council for Mineral Technology (MINTEK), as an entity of the DMR, is an organisation that carries out research and development for the mining industry as a national mineral research institution. The DMR also spearheaded the Mining Phakisa, which has increased beneficiation as one of its intended goals.

Implats and the IDC, along with a number of collaborators from government, industry and academia, have devised a roadmap that aims to propel the development of local manufacturing capacity of fuel cells. The roadmap also aims to achieve the localisation and commercialisation of fuel cell and fuel cell component manufacturing, with plans for a SEZ to be centred in Springs in Johannesburg (Impala Platinum Limited, 2016). The geographic location of such a SEZ is advantageous, as it will be located next to Implats’ refinery, allowing secure metal supply. Land will be granted by Implats in a region which is already industrialised and, thus, has fewer infrastructure requisites for the formation of a SEZ (Impala Platinum Limited, 2016). There is also a natural gas pipeline in the vicinity, therefore, security of gas supply is also certain, and the costs and logistics of having to transport gas are eliminated. In IPAP 2017/18-2019/20, efforts on key milestones will be from the IDC, DTI and industry on delineating crucial success factors, favourable technology collaborations and the supporting regulatory framework (Department of Trade and Industry of

South Africa, 2017c). Numerous strategies have been drawn up in order to overcome the existing barriers to local commercialisation. These include promoting market demand through demonstration projects that exhibit fuel cell technology, creating a local supply chain, and considering approaches required for acquiring capital requirements, particularly by way of developmental partners and government incentives (Impala Platinum Limited, 2016).

Implats has also been instrumental in spurring the fuel cell and hydrogen research and development plan through supporting research and development efforts through metal donations and loans (Impala Platinum Limited, 2017). Anglo American Limited (2017) indicated its intention to continue to promote South Africa as a manufacturing location and as a market for PEMFC products and also values the prospects of fast-tracking the localisation of fuel cell manufacturing. The successful electrification project that Amplats carried out in the Naledi Trust Community in the Free State demonstrated that fuel cell technology deployment in South Africa has the potential to stimulate a local fuel cell manufacturing industry and value chain. It also has positive implications for employment in parts fabrication, assembly, installation, servicing and maintenance as well as global export (Anglo American Limited, 2015a).

The Department of Science and Technology (DST) has co-ordinated a project, termed the National Hydrogen and Fuel Cells Technologies Flagship project, more commonly recognised as Hydrogen South Africa (HySA). HySA was launched in September 2008 and one of its obligations is to support South Africans in partaking in the commercialisation of fuel cell technologies (University of the Western Cape, 2017). This project comprises three Centres of Competence: HySA Catalysis, HySA Infrastructure and HySA Systems and its intention is to institute South Africa as a high-value product exporter in international fuel cell and hydrogen markets. It also intends to cultivate and channel innovation along the hydrogen and fuel cell technologies value chain locally and to, ultimately, direct South Africa's economy towards becoming a knowledge-based economy (Southern African Alternative Energy Association, 2017). In addition to the Centres of Competence that have been established for research, the DST has run public awareness campaigns which were aimed at touting hydrogen and fuel cell technologies as safe, clean and sustainable energy solutions (Cape Town Magazine, 2017).

HySA Catalysis is a research establishment responsible for the advancement of fuel cell and fuel to hydrogen technologies, with undertakings covering the spectrum from basic research to prototype development (Hydrogen South Africa Catalysis, 2017b). It has a handful of key academic and commercial goals. These goals include launching South Africa as a prominent global exporter of fuel cell components and catalysts and also developing the fuel cell supply chain in South Africa with local manufacturing partners. The intention is to achieve this while creating an internationally recognised hydrogen and fuel cell research organisation and developing human capital (Hydrogen South Africa Catalysis, 2017a). The focus of HySA Catalysis' research is largely on the early part of the value chain. HySA Catalysis works closely with the University of Cape Town and MINTEK, among other institutions (Hydrogen South Africa Catalysis, 2017a). Fuel cell related activities are centred on the enhancement of advanced catalyst, membrane electrode constructions for low-temperature polymer electrolyte fuel cell applications and electrode structures (Hydrogen South Africa Catalysis, 2017b).

The HySA Systems Integration and Technology Validation Competence Centre; known as HySA Systems in short; is co-hosted by the University of the Western Cape and the South African Institute of Advanced Materials Chemistry (SAIAMC). Its objective is to develop hydrogen fuel cell systems and prototypes and carry out technology validation and system integration. Essential technologies related to fuel cells are developed, prototyped, tried, validated and commissioned by HySA Systems. These include membrane electrode assemblies for high temperature PEM fuel cells, fuel cell stacks, lithium-ion batteries, system integration of energy storage devices and metal hydrides for hydrogen storage and compression (University of the Western Cape, 2017). The technical aims of HySA Infrastructure consist of developing hydrogen generation systems, hydrogen storage and distribution technologies and it works closely with North West University and the Council for Scientific and Industrial Research (CSIR) (Hydrogen South Africa Infrastructure, 2017). Amplats and HySA Infrastructure are also developing mining equipment powered by fuel cells (Department of Trade and Industry of South Africa, 2017b).

Another notable partnership has been between Implats and the DTI in making use of and developing local skills in fuel cell and hydrogen products, with the ultimate aim of accomplishing some of the strategic objectives of HySA (Fuel Cells Bulletin, 2012). This partnership saw Implats co-fund ZAR6 million towards a project that was carried out by HySA Systems. It entailed the investigation of innovative onboard hydrogen devices for use in portable applications such as forklifts, with Implats being a test site for these vehicles (Fuel Cells Bulletin, 2012). There is additional contribution to the development of local fuel cell technology applications from the mining sector from Amplats, which is financing research at HySA Catalysis, HySA Infrastructure and HySA Systems. This research involves a number of institutions and organisations such as MINTEK, North West University, CSIR, the Universities of the Western Cape and Cape Town and SAIAMC (Anglo American Limited, 2015b)

A foundation is being laid in South Africa for the rollout of fuel cell buses, with the DTI partnering with German collaborators to pilot fuel cell buses in South Africa (Cloete, 2017). It is expected that the buses, along with other mobile applications of fuel cells, such as load haul dumpers (LHDs) and forklifts, will spur platinum demand. Germany has advanced its fuel cell application in buses, having rolled out such buses in several cities, therefore making it an appropriate country from which South Africa can learn.

3.3. Conclusion

In this chapter, a global view of the development of fuel cell technology in recent years was taken. The nations and regions in which the technology has gained a great deal of traction were looked at and the efforts that they directed towards advancing this technology were detailed. In all of the nations where fuel cells are being introduced, manufactured and adopted with a notable degree of success, there is a marked collaboration between manufacturers and government to fast-track these advances. The common threads between all of these nations in their fuel cell and hydrogen ambitions are research and development, collaborative projects and partnerships and active government involvement. Locally, fuel cell technology has demonstrated a potential partner to gain in the mining industry, as has been demonstrated by Implats and Amplats.

The next chapter will go into the capital and operating costs that are associated with using a stationary fuel cell to power mining operations.

4. Economic Viability of Fuel Cells for Electricity Generation

4.1. Introduction

Currently, there is no South African manufacturing of fuel cells and all procurements of electricity generating fuel cells have been acquired internationally from a number of vendors and manufacturers. For this reason, this study was based on the acquisition of the fuel cells in the same manner for the two AngloGold Ashanti operations selected for the study. These two operations differ in terms of their use of electricity and there was a need to see what effect the difference in electricity utilisation would have on the outcome of the feasibility. The type of fuel cell which was considered was the MCFC since it is better suited for the stationary power supply applications upon which this feasibility study was focussed. Another reason that made the MCFC the most appropriate choice for this study is the large system range size of several MW that can be attained with the MCFC (Allen, 2012).

In this instance, a total fuel cell power consideration was studied, whereby power would be provided to fully run both sites. This is different from a baseload consideration, as baseload power is the minimum electrical power required for supply at a given time (Energy Education, 2017). The outcomes of this research were two-pronged. First, the feasibility of acquiring a fuel cell to power the two mining operations was determined. Thereafter, the prospects for local platinum beneficiation through the local manufacturing of fuel cells were discussed.

The acquisition of fuel cells for Implats and COM were facilitated with grant funding from the DTI and sourcing of government funding ought to be strongly motivated for. In the case of the former, the motivation was a drive to promote the local manufacturing, industrialisation and commercialisation of fuel cells while the latter had the goal of promoting local platinum beneficiation. In this context, AngloGold Ashanti is unable to make use of grant funding from the DTI because funding is granted only if the investment will directly bring about manufacturing and manufacturing investment. This procurement was, therefore, assumed to rely solely upon funding from a bank in order for the fuel cells to be acquired.

4.2. Fuel Cell Acquisition

4.2.1. Statement of Assumptions

In this feasibility study, the following were assumed:

1. Public data on the capital cost of acquiring fuel cells is not readily available. Therefore, the cost of the MCFC has been assumed from a chart that was produced by 4th Energy Wave (2015) to be USD2 386/kW (Figure 4.1). This interpolation is close to a figure of USD2 400/kW quoted by Remick and Wheeler (2010). For the purposes of simplified calculations, the latter figure was used. The total cost of acquisition, as well as operating costs for a MCFC, have been summarised from figures that were cited by Remick and Wheeler (2010) (Table 4.1).

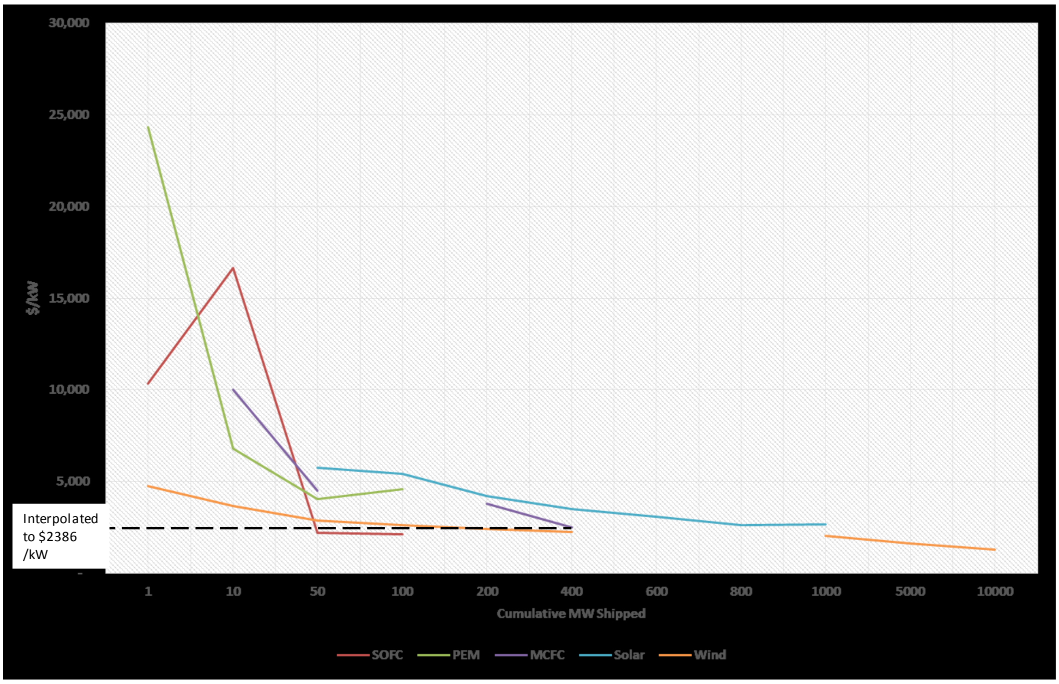


Figure 4.1: Interpolation of MCFC capital cost

Table 4.1: Capital costs associated with a Molten Carbonate Fuel Cell (Remick & Wheeler, 2010)

ITEM	COST (USD/kW)
Fuel Cell	2 400
Conditioning, Installation and Commissioning	700
Balance of Plant	1 100
Total Cost of Acquisition	4 200

2. The capital needed to acquire the fuel cell will be funded through 100% debt, through a bank loan that will be granted with an annual prime lending interest rate of 10.25% (Standard Bank, 2017), with equal monthly payments made over a fifteen-year period (annuity). The formula which was used to derive the monthly payment due is given in Equation 4.1.

Equation 4.1. Annuity payment calculation formula (Finance Formulas, 2012)

$$P = \frac{r(PV)}{1-(1+r)^{-n}}$$

Where:

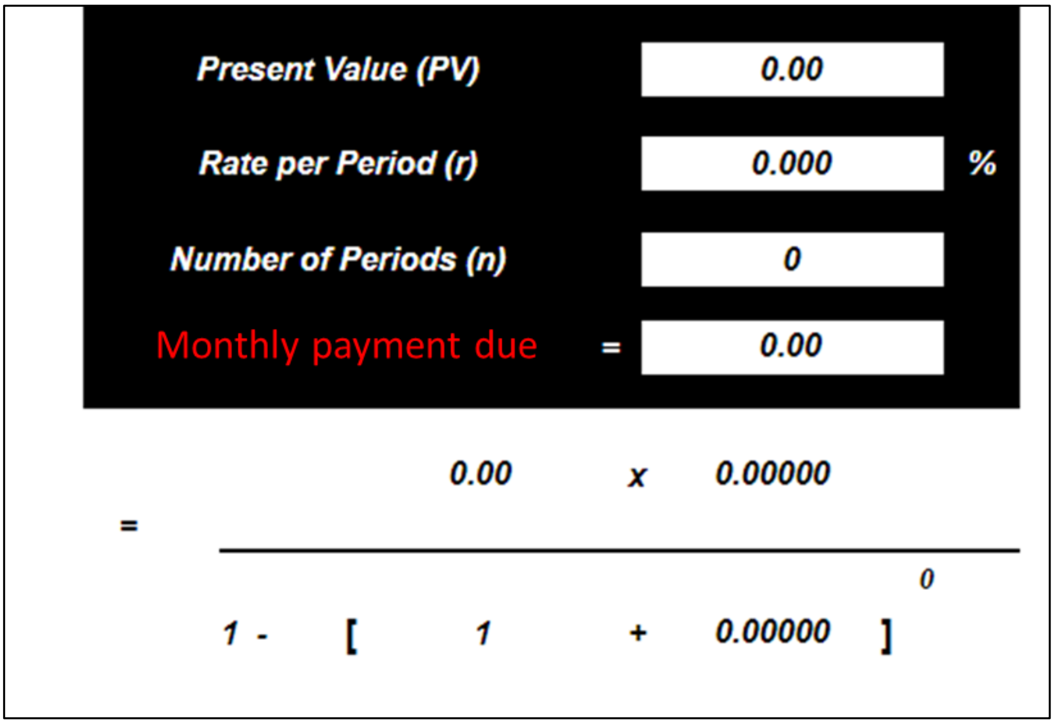
P is the periodic payment

PV is the present value (loan amount)

r is the rate per period (which will be equal to 0.0085416 for both operations)

n is the number of payment periods (which will be equal to 180 months for both operations)

These variables were input into an annuity payment calculator (Figure 4.2)



Present Value (PV) 0.00

Rate per Period (r) 0.000 %

Number of Periods (n) 0

Monthly payment due = 0.00

$$= \frac{0.00 \quad x \quad 0.00000}{1 - [\;1 \;+\; 0.00000\;]^{0}}$$

Figure 4.2: Annuity payment calculator (Modified from Finance Formulas (2012))

3. Gas supply for the Mponeng Complex will be from a nearby natural gas pipeline some 12km away which will be extended to the operation. The cost

associated with the extension of this pipeline and obtained from Egoli Gas is ZAR3 000/m (Egoli-Gas, 2017) and will cost ZAR36 million and will not be included in the acquisition costs. It is assumed that the pipeline extension will be paid for separately from the fuel cell acquisition. This separation of costs is carried out so that the cost of the acquisition of the fuel cell and the subsequent payments that will be carried out on it remain undistorted by associated ancillary capital expenditure. For Mine Waste Solutions, the nearest pipeline is over 100km from the site. In reality, the extension of the pipeline, costing more than ZAR300 million, would first have to be considered.

4. For the purposes of currency conversion throughout this study, one US dollar was fixed and equal to ZAR14.22 as quoted by Fusion Media Limited (2017).

5. For the Mponeng Complex, based on the load profile which indicates the electricity demand at various times (Appendix I), the size of the fuel cell that will be required will be 50MW.

6. For Mine Waste Solutions, based on the load profile which indicates the electricity demand at various times (Appendix II), the size of the fuel cell that will be required will be 30MW.

8. Where the operation of the fuel cells is concerned, the natural gas consumption will be scaled from the operating characteristics of the DFC300, a stationary MCFC power plant manufactured by FuelCell Energy and suitable for commercial and industrial purposes (FuelCell Energy Incorporated, 2010). The DCF300 is a 300kW fuel cell which makes use of a gas consumption of 39 standard cubic feet per minute (scfm) or 66 261.42 Litres per hour (L/h). In this study's calculations, the unit to be used was L/h.

7. The last assumption, which is fairly simplistic, is that the production profile of both operations will remain fairly consistent over the fifteen year period

over which the loan will be paid back, and, therefore, a regularity on the amount of electricity demand and consumption is assumed for each year.

4.2.2. Mponeng Capital Expenditure

For the Mponeng Complex, which has an electricity demand of 50MW, the total acquisition cost for a USD4 200/kW MCFC will be USD210 000 000 or ZAR2 986 200 000.

A financial institution granting a loan of ZAR2 986 200 000 at an interest rate of 10.25% over fifteen years and, with the annuity formula applied, yielded a fixed monthly payment of ZAR32 544 607 (Figure 4.3). The comparison between the monthly payments for a fuel cell was also made with an increased billing from Eskom which would result from a proposed 19.9% tariff increase (Singh, 2017). With such an increase, it becomes cheaper to pay the capital installment on a fuel cell than it is to be billed by Eskom only from the months of June to August. For the remaining nine months, a fuel cell is more expensive to pay off.

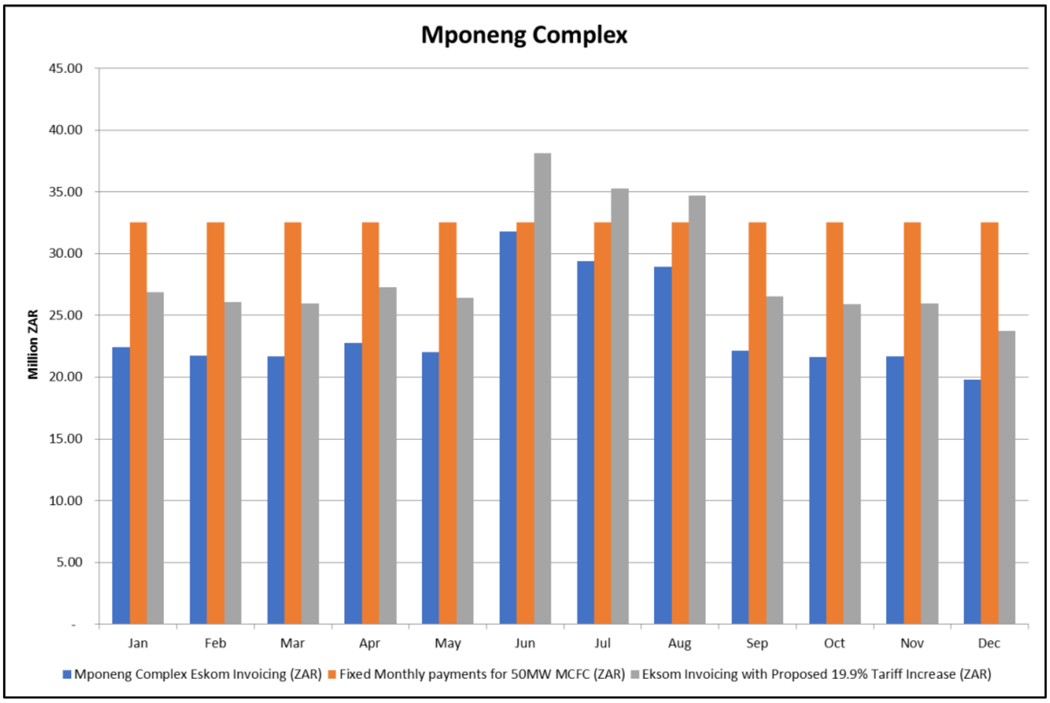


Figure 4.3: Fixed monthly payments of Mponeng Complex alongside current Eskom invoicing

4.2.3. Mine Waste Solutions Capital Expenditure

For Mine Waste Solutions, which has an electricity demand of 30MW, the total acquisition cost for a USD4 200/kW MCFC will be USD126 000 000 or ZAR1 791 720 000.

A financial institution granting a loan of ZAR1 791 720 000 at an interest rate of 10.25% over fifteen years and, with the annuity formula applied, yielded a fixed monthly payment of ZAR19 525 052 (Figure 4.4). The observation made in the case of Mine Waste Solutions is that only for three months in the year (June to August), is the capital cost of a fuel cell competitive with current Eskom billing. This is even more marked if the 19.9% tariff increase is applied, with the month of September almost also seeing fuel cells become a cheaper option than Eskom’s electricity.

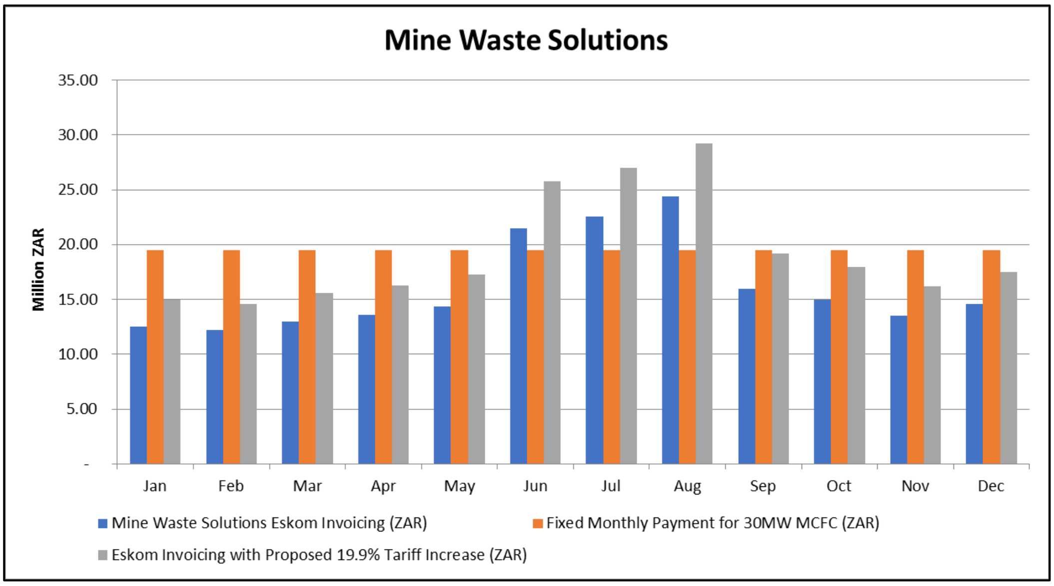


Figure 4.4: Fixed monthly payments of Mine Waste Solutions alongside current Eskom invoicing

4.2.4. Mponeng Complex Operating Expenditure

In order for the operating costs to be determined, it was first necessary to refer again to the electricity demand of each operation (Appendices I and II) so that the amount of gas that is required to be fed into the fuel cell could be deduced. From there, the costs associated with operation could be determined. A look at the demand for the Mponeng Complex demand profile shows that the demand follows a cyclical pattern. For the purposes of close demonstration, the profile was isolated over a two-day period (Figure 4.5).

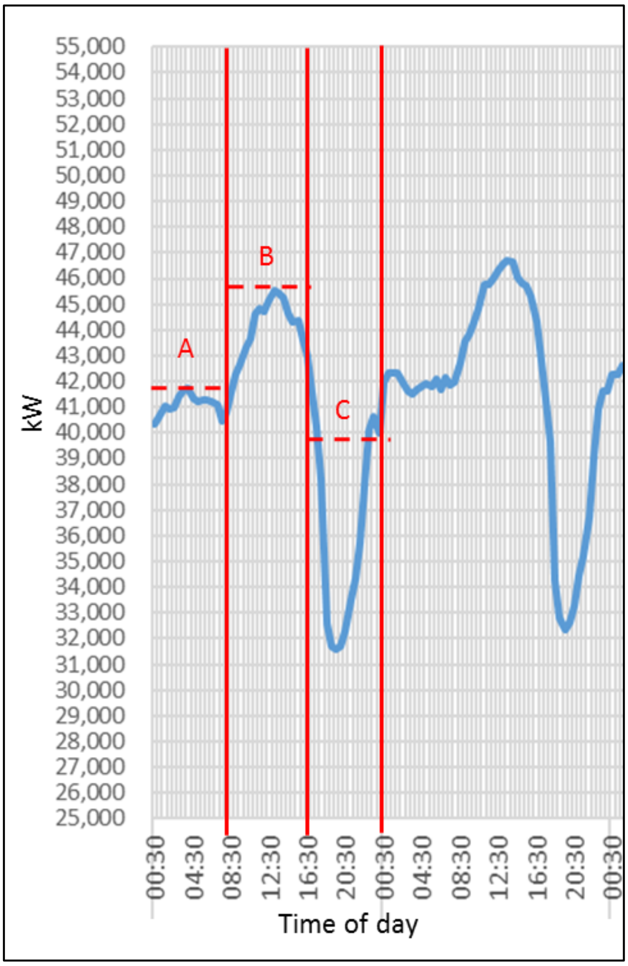


Figure 4.5: Two-day snap-shot of the Mponeng Complex's daily electricity demand

From the daily cycle, a division of three eight hour time periods was observed:

From 00:30 to 08:30, the demand is approximately 42MW.

From 08:30 to 16:30, the demand is approximately 46MW.

From 16:30 to 00:30, the demand falls sharply from 42MW to 31.5MW, before increasing rapidly again to 40MW. For this time period, the demand is put at 40MW.

The calculations used to compile the table have been listed (Table 4.2), allowing the total amount of gas consumed from the Mponeng Complex and the associated costs for this consumption to be broken down (Table 4.3). The number of full production days was assumed to be twenty-four days in a month, and the remaining six days include four Sundays out of the month and two alternating Saturdays (the other alternating Saturdays are production days). During non-production days, electricity is still needed for ventilation and pumping, amongst other uses, and the minimal demand of 40MW has been used to calculate the gas consumption of the fuel cell on these non-production days.

Table 4.2: Conversion factors used to calculate cost of natural gas

Parameter	**Conversion**
Scfm to Litre/hour	1 scfm = 1 699.01 L/h 39 scfm = 66 261.42 L/h (Convert Units, 2017)
Natural Gas Consumption (Litre/hour) on DFC300	DFC Scaling x 66 261.42
Litres (L) to cubic metres (m^3)	1 000 (1L = 1 000m^3) (Wight Hat Limited, 2017)
M^3 to Gigajoules (GJ)	25.5 (1m^3 = 25.5GJ) (Fortis BC, 2017)
Natural gas unit price (ZAR/GJ)	204.51 (as quoted by Egoli gas, 2017)

Table 4.3: Calculation of cost of natural gas for Mponeng Complex

Division	**Demand (MW)**	**Scaling from DFC300**	**Natural Gas Consumption (L/hr)**	**Natural Gas Consumption (L)**	**Natural Gas Consumption (m^3)**	**Natural Gas Consumption (GJ)**	**Price (ZAR)**
A: 00:30-08:30	42	140	9 276 599	74 212 790	74 213	2 910	595 124.10
B: 08:30-16:30	46	153.3	10 160 084	81 280 675	81 281	3 187	651 773.37
C:	40	133.3	8 834 856	70 678 848	70 679	2 772	566 901.72

16:30- 00:30							
Total daily natural gas expenditure (production day) = ZAR1 813 799.19							
Total natural gas expenditure over 24 production days = ZAR43 531 180.56							
Total natural gas expenditure over 6 non-production days = ZAR3 401 410.32							
Total typical monthly natural gas expenditure = ZAR46 932 590.88							

The months of January and December have three and eight fewer production days, respectively, owing to annual operations closures. These non-production days have been factored into the monthly operating costs (Figure 4.6).

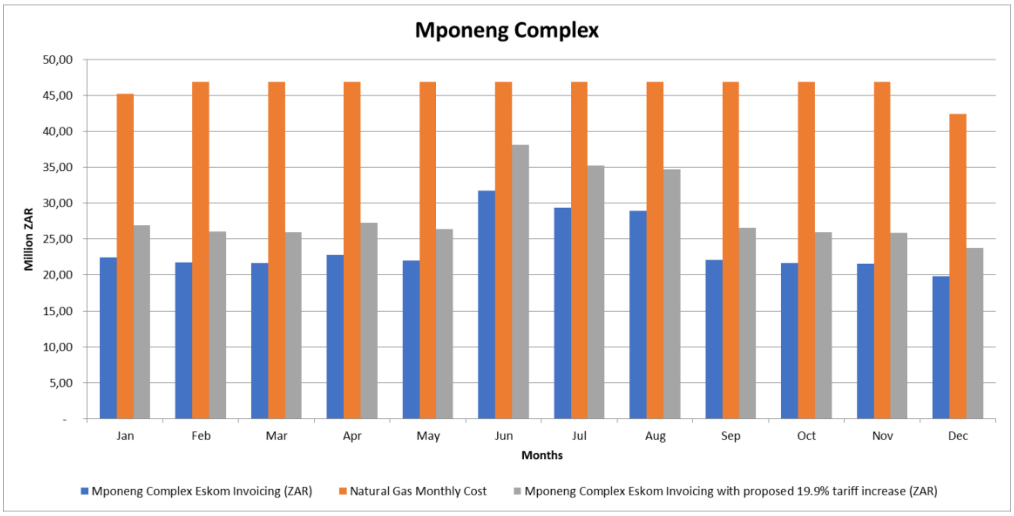


Figure 4.6: Operating costs of Mponeng Complex alongside current Eskom invoicing

4.2.5. Mine Waste Solutions Operating Expenditure

Mine Waste Solutions’ demand profile indicated that the demand for electricity remains fairly stable at approximately 25MW to 27MW (Figure 4.7). Two divisions over a twenty-four hour period were identified.

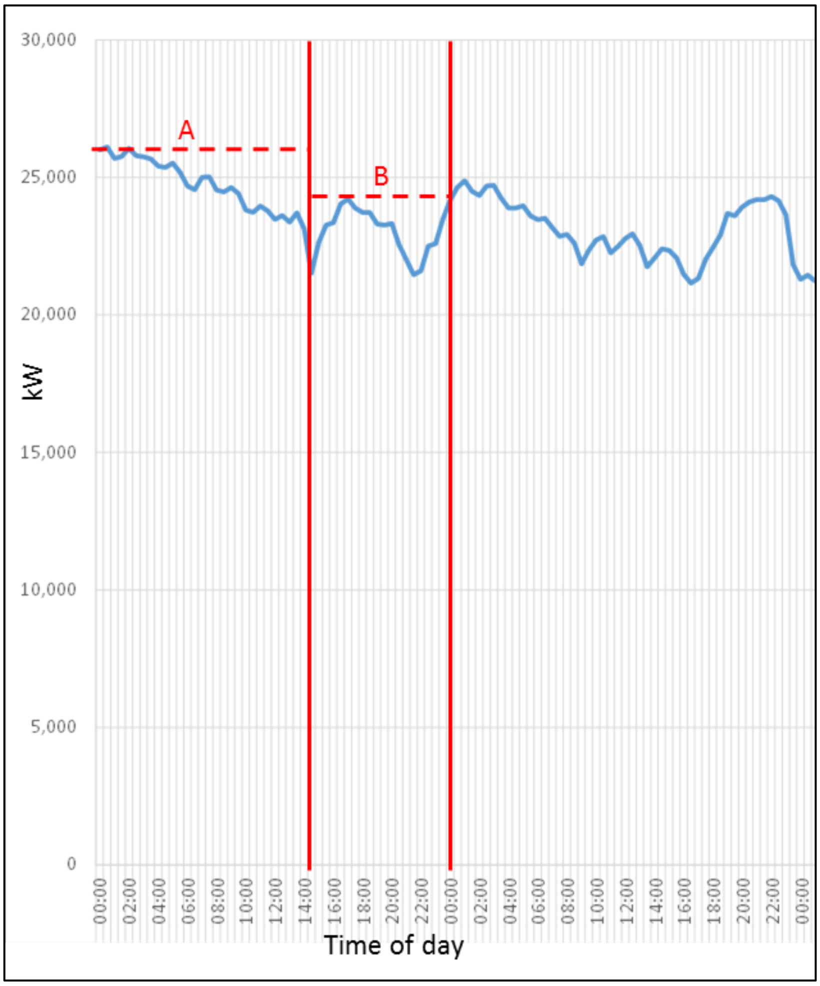


Figure 4.7: Two-day snap-shot of Mine Waste Solutions' daily electricity demand

From 00:00 to 14:00, a fourteen hour period, the demand is approximately 26MW.

From 14:00 to 00:00, a ten hour period, the demand is approximately 24MW or less.

Again, the different usage periods were used to derive the consumption of natural gas over a given time (Table 4.4).

Table 2.4: Calculation of cost of natural gas for Mine Waste Solutions

Division	**Demand (MW)**	**Scaling from DFC300**	**Natural Gas Consumption (L/hr)**	**Natural Gas Consumption (L)**	**Natural Gas Consumption (m^3)**	**Natural Gas Consumption (GJ)**	**Natural Gas Price (ZAR)**
A: 00:00- 14:00	26	87	5 742 656	80 397 190	80 397	3 153	644 783.94
B: 14:00- 00:00	24	80	5 000 914	53 009 136	53 009	2 079	425 132.18
Total daily natural gas expenditure (production day) = ZAR1 069 916.12							
Total natural gas expenditure over 24 production days = ZAR25 677 986.88							
Total natural gas expenditure over 6 non-production days = ZAR2 550 793.08							
Total typical monthly natural gas expenditure = ZAR28 228 779.96							

Again, the three and eight days of non-production were removed from the months of January and December, respectively. The cost of natural gas was compared to current Eskom invoicing for Mine Waste Solutions (Figure 4.8).

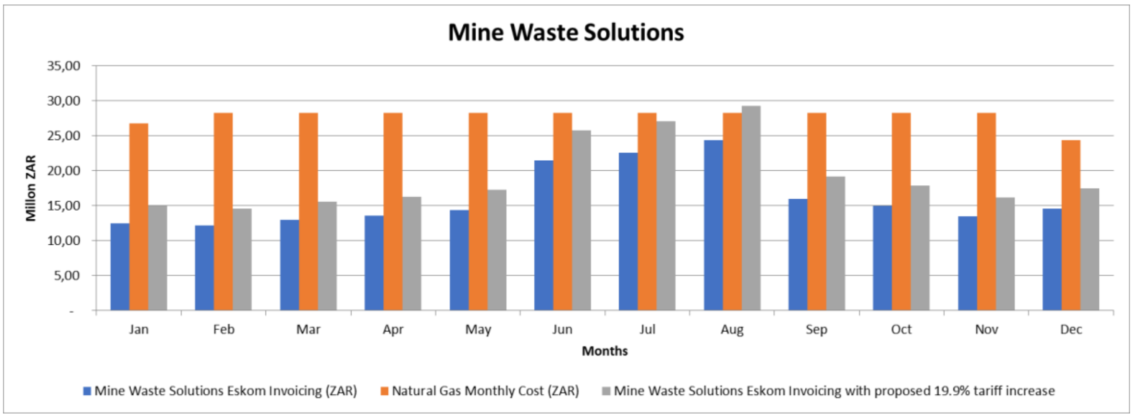


Figure 4.8: Operating costs of Mine Waste Solutions alongside current Eskom invoicing

It should be noted that, although the calculations of Mine Waste Solutions' operating expenditure were based on the grounds that gas would be sourced from a pipeline in the vicinity, there is no natural gas pipeline in the vicinity of Mine Waste Solutions. An alternative for gas supply is for gas to be transported in the form of liquid petroleum gas (LPG) to the site where it is needed. If gas were to be transported by a company such as Afrox, an industrial gas supplier in the region, the cost would be ZAR9 03.87, excluding VAT, for the refill of a 48kg cylinder (Afrox, 2017). According to Elgas (2017), 1kg of gas yields approximately 49MJ of energy. Therefore, a 48kg cylinder of natural gas would contain 2 352MJ or 2.35GJ. If the natural gas consumption of Mine Waste Solutions on a full production day is 5 232GJ, then the total number of 48kg gas cylinders required would be 2 226, at a daily cost of ZAR2 012 360.

4.2.6. Summary of Findings

The findings of this feasibility study have indicated that a stationary fuel cell would not be economically viable for either of the two study sites, neither in terms of the capital cost nor in terms of the operational costs. The outcomes of this study strongly suggest that fuel cell technology, in the stationary, industrial application is currently not at the stage where it can be deemed competitive with conventional coal-generated electricity on a mining operation.

For both operations, gas pipelines would have to be extended. For these extensions to be warranted, the consumption of natural gas would have to make financial sense in that it would have to be cheaper than the current Eskom cost to the company. Since this is not the case, it is unlikely that the extension of the gas pipes could be motivated for. The logistics of transporting gas in cylinders are also too costly (more costly than using piped gas). The observation of operating costs being prohibitively high is in contrast to what has been observed in previously mentioned applications, where the expected outcome is that a high capital cost can be motivated for because of the cost saving that is seen with the operation of the fuel cell.

Lastly, when evaluating the two operations’ fuel cell feasibility, an interest was on the comparison of the outcomes. The expectation was that Mine Waste Solutions, which does not use as much power as the Mponeng Complex, would have a greater prospect of feasibility. However, this was not the case. All but one of the months of production saw expenditure in favour of Eskom rather than a fuel cell for operating costs and only a quarter of the year for capital costs were in favour of the fuel cell.

4.3. Conclusion

The purpose of this chapter was to determine the economic feasibility of acquiring large, stationary fuel cells with which to power two mining operations: a deep level gold mine and a surface stockpile processing operation. Demonstration of the likelihood of successful adoption may have acted to catalyse a local manufacturing industry. The reason for which the two different sites were selected for the study was to determine if the intensity of power use would influence the feasibility of acquiring a stationary fuel cell. The deep level underground mine utilises and relies on far more electrical power than the surface operation. The outcome of the study is that the acquisition of a stationary fuel cell for either site is economically unviable; both in terms of capital expenditure and in terms of operating expenditure and is uncompetitive with the current coal-generated electricity supplied by Eskom. This finding differs from the commonly stated testimony that although fuel cells have high capital costs, a cost saving is seen at the back end with their relatively lower operating costs.

Nonetheless, fuel cells have a far wider range of applications than the industrial, stationary application that was the subject of this chapter. Through these other applications via which small-scale adoption may take place, manufacturing still has the potential to contribute to the domestic economy, through platinum beneficiation and their export into the global market. Mining companies such as Implats and Amplats have demonstrated the considerable scope that exists for the use of fuel cell technology. The next chapter will outline the competencies that need to be developed by South Africa while advancing toward a stage where local fabrication of fuel cells may be attained. Observations from other nations that have successfully established manufacturing, detailed in the previous chapter, will be strongly relied upon.

5. Discussion of Findings

5.1. Introduction

The preceding chapter entailed determining the feasibility of acquiring fuel cells to power Mponeng Gold Mine and Plant as well as Mine Waste Solutions. It was revealed that the capital and operating costs of acquiring a fuel cell are greater than that of sourcing electricity from Eskom. The outcome of this economic feasibility study is discussed in this chapter.

Additionally, this chapter explores the prospects that exist for South Africa to manufacture fuel cells locally. Fabrication is the most economically advantageous stage of the mineral beneficiation stage. Consequently, it brings with it the most significant creation of employment and can potentially bolster economic development.

5.2. Feasibility of Fuel Cell Technology on Study Sites

There is a strong indication that the capital cost of acquisition is still a significant barrier to adopting stationary applications of fuel cell technology. Even when a scenario of a 19% electricity tariff hike by Eskom is deemed a threat that would cripple the economy and business (Singh, 2017), the expenditure on a fuel cell is still significantly more costly. This is more marked for the Mponeng Complex. It should be considered that even the purchases of fuel cells for the COM and Implats were heavily reliant on funding and may not have taken place had they been carried out as unassisted projects. Furthermore, both sites were advantaged by their locations being close to natural gas pipelines. It is hoped that the capital and operating costs of fuel cells will be significantly reduced with economies of scale as well as technological advances that increase the stack life and power density, with

Remick and Wheeler (2010) anticipating that costs will be reduced to just over USD3000/kW by 2020 and to USD2000/kW by 2030. Local manufacturing would also contribute to a lower capital price for a fuel cell, as local manufacturing costs are expected to be lower than the international average. A ZAR pricing of the locally produced fuel cell may additionally act to remove the volatility and increased price that is attached to an exchange rate with a fuel cell produced abroad.

5.3. Fuel Cell Manufacturing in the South African Context

As has been previously mentioned, South Africa is not yet at a stage whereby fuel cell manufacturing is local. If the mineral value chain is to be considered, the highest number of jobs created (and, accordingly, the greatest degree of economic stimulation and development) is at the point at which products are fabricated. Thus, the goal of platinum beneficiation for South Africa ought to go beyond only processing to manufacturing. The fabrication stage of the mineral value chain is also that which entails a great clustering of inputs such as skills, research and development, infrastructure and capital. However, barriers which need to be overcome for manufacturing to take place need to be acknowledged and addressed. South Africa is known to have a wealth of mineral resources which can certainly spur resource-based industrialisation. In the case of this study, South African platinum could potentially prompt local fuel cell manufacturing. According to the Department of Trade and Industry of South Africa (2017b), the national goal is for South Africa to attain a 25% share of the worldwide fuel cell market.

Several barriers that may pose a hindrance to increased resource-based industrialisation and the lessons that can be learned from other nations where similar hindrances were overcome will henceforth be deliberated. They include the availability of necessary skills, infrastructure, raw materials and capital, industry-government-academia collaboration and research and development. From this discussion, the competencies which first need to be developed for local fuel cell manufacturing to take place will be deduced.

5.3.1. Skills

A wide range of skills is required to build a local fuel cell manufacturing capacity. A South African undertaking in fuel cell manufacturing may not follow an identical path as that of the USA. Nevertheless, the skill set listing (Table 3.1) is useful in gaining an understanding of the fundamental skill set that would be required for that goal to be attained. The importance of investment in skills, knowledge and training cannot be over-emphasised. One of the ways in which these skills can be cultivated is through internship programs that could be offered by companies such as IPM, targeted towards the broad spectrum of graduates that will have the requisite qualifications and will be in need of specialist training.

As the DST has led the initiative of advancing a knowledge-based economy in the fuel cell industry, a graduate skills training initiative could be considered as an additional programme until such a time that local fuel cell manufacturers are able to carry out their own skills development programmes. The South African Agency for Science and Technology Advancement (SAASTA) has run a number of public awareness campaigns which detail the academic institutions that are involved in or have collaborated in hydrogen and fuel cell technology research. These institutions can, through their research programs, assist in building the skill set needed to support a fuel cell manufacturing industry. The USDOE's method of providing training to untrained instructors from experienced facilitators is one supplementary approach that can be considered in an early local fuel cell industry. In this instance, technical expertise could be provided by academia and professionals specialising in fuel cell and hydrogen systems. In this way, a company such as IPM could identify how many skilled professionals it would need to have in order to expand its activities from fuel cell component manufacturing to outright fuel cell manufacturing. Investment in current and future labour (potential candidates from academic institutions working towards the various, relevant qualifications suited to fuel cell manufacturing) would allow it to accumulate the necessary skills for its manufacturing from academia and specialised professionals. This would assist in making the company ready for expansion into complete fuel cell manufacturing.

Further support could be sought by South Africa’s DTI and DST from North American, Asian and European institutions which have benefited from specialist training in nations whose fuel cell industries are more advanced. Steyn (2015) stated from survey results released by Manpower South Africa that there is a significant demand for engineers and skilled trade workers who form the bulk of the skillset required for a fuel cell industry. Employers are finding it increasingly challenging to fill vacancies of these skills. Other skills which encounter similar problems and form part of the set necessary for fuel cell manufacturing include management, administrative and finance staff and technicians. A paucity of industry-specific qualifications and experience were among the reasons highlighted for the difficulty employers have in filling vacancies. This is coupled with the nation’s high poverty levels which render many incapable of pursuing secondary and tertiary education. This shortage of skill and talent is being addressed largely by companies undertaking to train and develop existing staff (Steyn, 2015).

5.3.2. Infrastructure, Raw Materials and Capital

Collier (2014) highlighted the dependence of international trade on infrastructure. Mitochondria Energy and Implats, both cited by Oliveira (2015) stated that the most critical infrastructure to the development of a fuel cell manufacturing industry is the availability of gas feedstock. Currently, South Africa imports a significant amount of its gas from neighbouring Mozambique. In order for South Africa to develop its gas infrastructure to such a degree that the local manufacturing of fuel cells can be supported and sustained through a small domestic market, the current infrastructure must first be assessed for its capacity. The additional capacity required, if any, can then be quantified and a plan put into place on how the capacity will be sourced.

South Africa could benefit from investor capital into its natural gas if policy uncertainty could be swiftly addressed. Arnoldi (2017) made mention of sluggish and delayed developments on documents that are to provide direction on the development of the gas sector. These include the Gas Utilisation Master Plan (GUMP), the Mineral and Petroleum Resources Development Amendment Act (MPRDAA) and the Renewable Energy Independent Power Procurement Programme (REIPPP). GUMP, which has been in the planning phase since 2012 (Van Wyngaardt, 2016), is a strategic plan owned, established and applied by South Africa’s Department of Energy (DOE). It details South Africa’s intentions to integrate gas into the energy blend through public-private partnerships (Arnoldi, 2017), and is a long-term roadmap for the tactical expansion of natural gas demand and supply (Bischof-Niemz, et al., 2016). Investor sentiment is greatly affected by political uncertainty, moreso than it is by project costs or timelines (Van Wyngaardt, 2016). South Africa’s prospects for investment security will be greatly improved if efforts on policy clarity and certainty are expedited so that investor confidence can be tenable.

A significant amount of capital is injected into an industry through investment. As of late, South Africa's standing as an investment destination has been adversely affected by recent investment rating downgrades. Perceived political risk and uncertainty, and underperforming economic indicators, such as slowed economic growth with a weak outlook and fiscal challenges have resulted in a junk status sovereign rating from several major global rating agencies. The reason a sovereign credit rating of junk is of significance in the context of capital acquisition is that potential investors use ratings to inform their investment decisions in countries or businesses (Modise, 2017). For the government, the implication of a rating downgrade is that more money is allocated to servicing debt costs due to higher interest on its debt (as a result of higher risk perception). This leaves less money available for investment priorities, employment creation and, ultimately, GDP growth potential (Modise, 2017). It is for this reason that efforts from the government are required to restore investor confidence in the country. Initial steps would be to ensure political and policy certainty, to minimize changes in policy objectives and recurrent changes of leadership that have been seen in key ministries lately and to implement the structural reforms that are required for economic growth (Donnelley, 2017).

5.3.4. Multi-stakeholder Collaboration (Government-Industry-Academia)

Collaboration between manufacturers and Original Equipment Manufacturers (OEMs) will aid in allowing development and advancements in fuel cell technology to be made. A prominent example of this is in the mobile applications, where fuel cells can potentially be used on buses and cars. The developers and specialists of fuel cells are not competitive in vehicles and, thus, would need the buy-in of the relevant OEMs in testing these applications. Buses have been regarded as an avenue through which the mobile applications of fuel cells can be utilized. A local market for fuel cell buses may act to catalyse a local manufacturing industry which would then also cater for the global market.

There is considerable opportunity for government's role in promoting fuel cell technology through mobile applications in buses. A malleable path through which to start is the Bus Rapid Transit (BRT) system, a public transport system rolled out by the City of Johannesburg in 2006-2007 and commonly referred to as Rea Vaya. According to Rea Vaya (2017), the BRT system was touted through research by the City of Johannesburg to have the potential to contribute to reduced greenhouse gas emissions. It was stated that if the bus system was made use of by fifteen percent of Johannesburg's car users, Johannesburg's carbon equivalent emissions could decrease by 1.6 million tons by 2020. Since cleaner energy is one of the mandates of Rea Vaya, it would be worthwhile for the City of Johannesburg to carry out feasibility work which would indicate the prospects of fuel cell buses. These buses could be tested and added to the existing Rea Vaya fleet. While the fuel cell buses are being developed, early-stage investigations into the minimum amount of hydrogen refuelling stations should simultaneously be carried out. This will ensure that any potential roll-out of fuel cell buses is not impeded by the lack of refuelling sites.

The government would do well to lead by example in using fuel cell technology in applications such as vehicles, as has been done in Japan, and state buildings, as has been done in the USA. For a small, local fuel cell market, the state may be able to assist in propelling a momentum in fuel cell technologies. For instance, a small fleet of fuel cell powered government vehicles may be acquired to satisfy a host of significant objectives. These include proof of reliability of fuel cells, creation of economies of scale, encouragement of platinum beneficiation, catalysis of a local fuel cell market, incentive for hydrogen refuelling stations which will further support a local market and palpable efforts to reduce greenhouse gas emissions. A second example for South Africa's government to follow is the compilation of a strategic roadmap similar to what the Japanese Ministry of Economy, Trade and Industry (METI) compiled. Such a roadmap would have clear timeframes and detailed phases and defined targets for the competencies required for local fuel cell manufacturing to be developed. METI's roadmap was concerned with fuel cells in vehicles and in homes, but applied locally; such a detailed roadmap would be dealing largely with the structures required for local manufacturing to be implemented.

Where mining could further amplify the space for the growth of fuel cell technology is in mechanization. As it stands, a Mining Precinct has been established in Johannesburg. Through private-public collaboration, this Precinct aims to develop new mining technology and techniques to overcome current barriers being faced in the mining industry (Slater, 2016). Research into the use of fuel cell technology in mechanised mining equipment and machinery, such as automated trucks and drill rigs, should be made one of the focuses of growing mechanisation in South Africa's mining industry. The platinum mining industry has conceded that mechanisation of mining operations will become increasingly widespread in order for operations to remain profitable (Solomons, 2016). The gold mining industry faces a similar challenge in declining production if mechanisation levels remain low (Figure 5.1) (Seccombe, 2017). Mining Online (2016) stated that the development of new technology in mining could drive the expansion of a local manufacturing industry for machinery. This is something that creates an opportunity for a fleet of machinery that could potentially run on fuel cells.

Figure 5.1: Production profiles of platinum and gold with varying degrees of mechanisation (Chamber of Mines as cited by Seccombe, 2017)

Again, involvement from and collaboration with OEMs such as Caterpillar Incorporated and Komatsu Limited, both manufacturers of mining equipment and machinery, will aid the development process. A portion of investment into the fuel cell manufacturing industry could be used to subsidise OEMs who get involved in using fuel cell technology. This would be incentive for their involvement and would allow for the risk and cost associated with nascent technology to be shared amongst multiple stakeholders. Efforts to carry out research and development and viable adoption of fuel cell technology within the scope of mechanized mining are likely to garner support from the government. Firstly, from the active research that is currently being carried out in collaboration with mining houses. Furthermore, from the funding allocation that is granted by the DTI if projects will promote platinum and encourage or lead to local manufacturing. Efforts to expand local manufacturing of machinery while extending the life of mining operations and, consequently, contributing to economic growth and development of the country should be amongst those prioritised for the State's support. The same support should also be afforded to efforts to attain a low-carbon emission economy.

Where policy and regulatory framework are concerned, in as much as South Africa's mineral policy encourages downstream beneficiation; efforts towards mineral beneficiation through fabrication should be directed toward interested potential manufacturers. The effort has traditionally been to encourage downstream value addition through mineral processing. The stage of beneficiation that involves fabrication is removed from mineral extraction to a considerable degree. It seems, then, that the role of mineral policy in this context is secondary to that of industrial policy. The policy on the development of SEZ in South Africa was one such significant policy action in that it gives incentives through special concessions and motivations to those interested in setting up manufacturing.

5.3.5. Research and Development

Essentially, there are several robust structures which exist to support the local manufacturing of fuel cells in South Africa. These exist in the form of research and development through various academic institutions. Support from the DST, project funding from the DTI, and involvement from private companies in the form of the testing, development and acquisition of fuel cell applications sustain research and development.

Research is essential not only in the technical aspect of fuel cell technology, but also in the economic sphere. It is essential to know the point at which economies of scale will be attained in manufacturing so that a yardstick for the manufacturers can be defined. The development of a model similar to what was developed by ANL for the USDOE's FCTO in the USA with parameters specific and relevant to South Africa would be invaluable. Such a model would enable government and industry to determine in which way funding and efforts should be focussed and allocated for the greatest benefit to be realised from fuel cell manufacturing.

Lastly, it is essential that the state of market willingness is ascertained; especially where hydrogen infrastructure is concerned, since the sustenance of a fuel cell market is highly dependent on the supporting hydrogen infrastructure. This is a feat that is achievable through a series of engagements that would be attended by various key ministries such as trade and industry and energy, industry representatives from the fuel cell manufacturing sector and OEMs.

5.3.6. Platinum Beneficiation with Local Manufacturing

According to Creamer (2017b), fuel cell vehicle sales in Japan, which are expected to increase significantly, will boost the demand of platinum, as would the introduction of heavy-duty fuel cell vehicles in China. A demand of approximately 500 000oz of platinum by 2025 is likely to result from China and Japan's strong lead towards fuel cell technology (Creamer, 2017b). This also creates a larger global market of which South African fuel cell stacks could supply a portion of. A concurrent feat of further value addition in the form of local fuel cell manufacturing would result in increased platinum demand than what is currently anticipated.

5.4 Conclusion

This chapter detailed the proficiencies that are required to establish a local fuel cell manufacturing industry. It also acknowledged the efforts that have been put in by various ministries into developing such an industry. The local fuel cell manufacturing industry stands to gain support from the DTI through a number of structures. These are the provision of SEZ, and also through the DTI placing increased focus on fuel cells as they have outlined in their latest IPAP. In addition, the DTI’s efforts to acquire knowledge from nations such as Germany, which have matured their applications and expertise in fuel cells, will aid local attempts. Such international relationships should be used as far as possible to expand South Africa’s nascent skills base to complement companies such as IPM once they are ready to expand into outright fuel cell manufacturing.

In supporting and encouraging the growth of a local fuel cell market, government will have an invaluable role to play in drafting and finalising the right legislative and regulatory framework. Ideally, this framework will attract investors and bolster investor confidence for the expansion of the natural gas infrastructure that will support the growth of a fuel cell manufacturing industry.

Fuel cell manufacturing has a potential partner to gain in the mining industry, as has been demonstrated by Implats and Amplats. The acquisition of a stationary fuel cell to power a mining operation is currently not feasible due to the prohibitively high capital and operating costs. These costs could potentially decrease with economies of scale, technological advancements and the cheaper manufacturing costs resultant from local manufacturing. Nevertheless, mobile applications of fuel cells on mining operations have greater prospects, through LHDs, forklifts and even locomotives. A third partner in this venture would be the OEMs which provide such mobile equipment to the mining operations and opportunities for collaborative work in the mining industry’s current drive toward mechanisation can be created.

6. Conclusion and Recommendations

6.1. Discussion

The foundation of this study has been on the use of fuel cell technology as an avenue for increased platinum beneficiation and, consequently, economic development. With regards to mineral value addition, the highest potential for employment creation and resultant economic development lies at the end of the value chain with fabrication. The intention of this study was, therefore, to ascertain the prospects that exist in South Africa for platinum beneficiation through the local fabrication of fuel cells. The study entailed establishing the feasibility of using fuel cells to power two of AngloGold Ashanti's mining operations. These were the Mponeng Complex, which consists of the Mponeng deep level underground gold mine and its plant, and Mine Waste Solutions, a surface stockpile processing operation. The premise of this feasibility study was that acquiring a fuel cell for a large, industrial operation such as a mining operation would lead to small-scale, local adoption that could spur a local manufacturing industry. The specific type of fuel cell most suitable for large-scale, industrial, stationary power supply (a molten carbonate fuel cell) does not make use of platinum in its stack. Nevertheless, successful adoption of any type of fuel cell will encourage the consideration of the adoption and implementation of all other types, including those that use platinum as a catalyst.

The importance of this research was cited as the need to explore further platinum downstream beneficiation in the form of fuel cell manufacturing, which has relevance in the current state of the South African economy. It was also to provide understanding on alternative energy sources in the face of rising domestic electricity costs and concerns around reliable power supply, climate change and the environment.

Fuel cells generate energy from electrochemical reactions that take place between an anode and a cathode, using hydrogen and combining it with oxygen to produce electricity, heat and water. A cell comprises two electrodes, and when these cells are arranged in series, they are referred to as a stack. Fuel cells have been touted for their relatively higher efficiencies resulting in lower operating costs, their low maintenance, their quietness and reliability, wide range of applications and their minimal emissions. Their environmentally friendly quality is especially advantageous in the current global drive to reduce greenhouse gas emissions which are responsible for climate change. However, they face a challenge in their prohibitively high capital costs which need economies of scale and a reduction in the cost of their materials to be overcome. In the global ambition to acquire energy from more environmentally friendly sources, renewable energy has also been looked to.

Mineral beneficiation has legislative and regulatory support in South Africa in the form of various policy documents. These documents include the MPRDA, the Minerals and Mining Policy for South Africa, the Precious Metals Act, the Industrial Policy Action Plans and the South African Mining Charter. There are several national economic and social development plans such as the Beneficiation Strategy, the National Industrialisation Program and the National Development Plan. South Africa’s 87% share of the world’s PGM grants it a comparative advantage for increased platinum beneficiation. Industrial policy has been cited as a strong influencer in the success determinant of resource-based industrialisation. The establishment of SEZ may act to incentivise investment in local fuel cell manufacturing. In this regard, industrial policy is a more substantial support tool because of the fabrication associated with this stage of value-addition. Greater focus should, therefore, be placed on it as it is removed from mineral extraction to a significant degree. China and Japan’s strong drive towards acquiring fuel cells will increase the beneficiation of platinum, and will also create a global market of which South Africa can become a part.

Market analysis of fuel cell technology indicates that there is anticipation for an increase of the value of the market. However, fuel cell manufacturers have struggled to realise profits, largely due to the need for mass manufacturing. Mass manufacturing would require scaling up of investment, staffing and infrastructure, which would impact on the manufacturers’ bottom lines. The development of more stringent emission regulations in various nations is one of the driving forces behind increasing fuel cell adoption, and the most common use for fuel cells is in stationary applications. The general expectation of the capital cost of fuel cells is that it will eventually decrease as the technology advances and as distribution increases. The regions that dominate the fuel cell market are North America, Asia and Europe. South Africa currently has no fuel cell manufacturer. A common observation has been that the gains that are made in fuel cell technology are made possible by close collaboration and partnership between private stakeholders and government, with a significant investment in research and development.

6.2. Conclusion

The result of the feasibility study of powering two AngloGold Ashanti operations with a stationary fuel cell revealed that, currently, it is not economically feasible to purchase a fuel cell for either a deep level gold mine or a surface processing operation. This is due to the high capital costs. Furthermore, the operating costs associated with the fuel cell, which come from the cost of natural gas, are also not competitive with the current invoicing that both operations receive from Eskom. Despite the marked adoption of fuel cells in a range of applications, sourcing a fuel cell to provide primary power on mining operations is unlikely to take place on the two sites selected for this study.

However, fuel cells have been successfully functional in other spheres and applications and still have a scope for adoption in buses, cars, and mechanized mining equipment, amongst others. There is, therefore, still potential for the beneficiation of platinum to be seen in the local manufacturing of fuel cells for small-scale local adoption and for export into the global market. This is particularly marked in the modernisation and mechanisation of South African mines, an avenue through which significant room for research exists. Mining has, thus, been identified as a strong potential conduit through which domestic manufacturing can be enhanced. Local manufacturing prospects are further bolstered by South Africa’s relatively cheaper manufacturing costs compared to the rest of the world and the availability of SEZ. South Africa has established fundamental proficiencies through research and development and collaborations with mining houses such as Amplats and Implats and with pronounced support from the DTI and DST. Additional consultation with nations that have advanced their fuel cell industry, notably, North America, Germany and Japan, will only act to further strengthen these competencies.

What can be concluded from this study is that fuel cell technology in the South African setting is still an infant technology and, to its advantage, it has the support of industry, academia and government. It needs increased demand and for capital costs to come down, making prospects for increased platinum beneficiation through it reliant upon further research and development and demonstrations at this stage. Increased demand and lower capital costs are reciprocal, as economies of scale created by increased demand will act to drive capital costs down. What will be of great importance in reducing capital costs is further research and development in creating fuel cell stacks which have longer lifespans and are cheaper to produce. A second balance that has to be struck is that of the amount of platinum used in the fuel cell, which contributes to the high capital cost. In addition, reducing the required amount without disadvantaging the platinum industry is necessary so that platinum beneficiation through fuel cell manufacturing can still be maintained.

6.3. Recommendations

What can be recommended from this study is the continuation of research and development that will result in reduced capital costs of the fuel cell, which will encourage increased adoption of the technology, locally and globally. Research towards increased fuel efficiency will also go a long way towards decreasing operating costs. Sites such as the COM building and Implats, where operating costs have made the use of fuel cells feasible, owe this feasibility to the close proximity of natural gas pipelines to them. Therefore, an investigation into alternative gas supply for operating sites situated far from gas supply networks, where bottled gas will be too heavy a logistical cost, will also aid in reducing gas costs for operations such as Mine Waste Solutions. Further recommendations are for more tangible government participation in advancing fuel cells. This would be achieved through acquiring, demonstrating and supporting fuel cells by applications such as buses and cars, while articulating detailed deliverables and targets on the development of a fuel cell manufacturing industry. Policy action plans around fuel cell manufacturing ought to have clear, quantitative targets, even if outlined in a series of phases, for plans to stand a better chance of being implementable. Demonstrations by companies making use of fuel cell technology should be continuously carried out so that wide-scale public support and acceptance of the technology can be gained.

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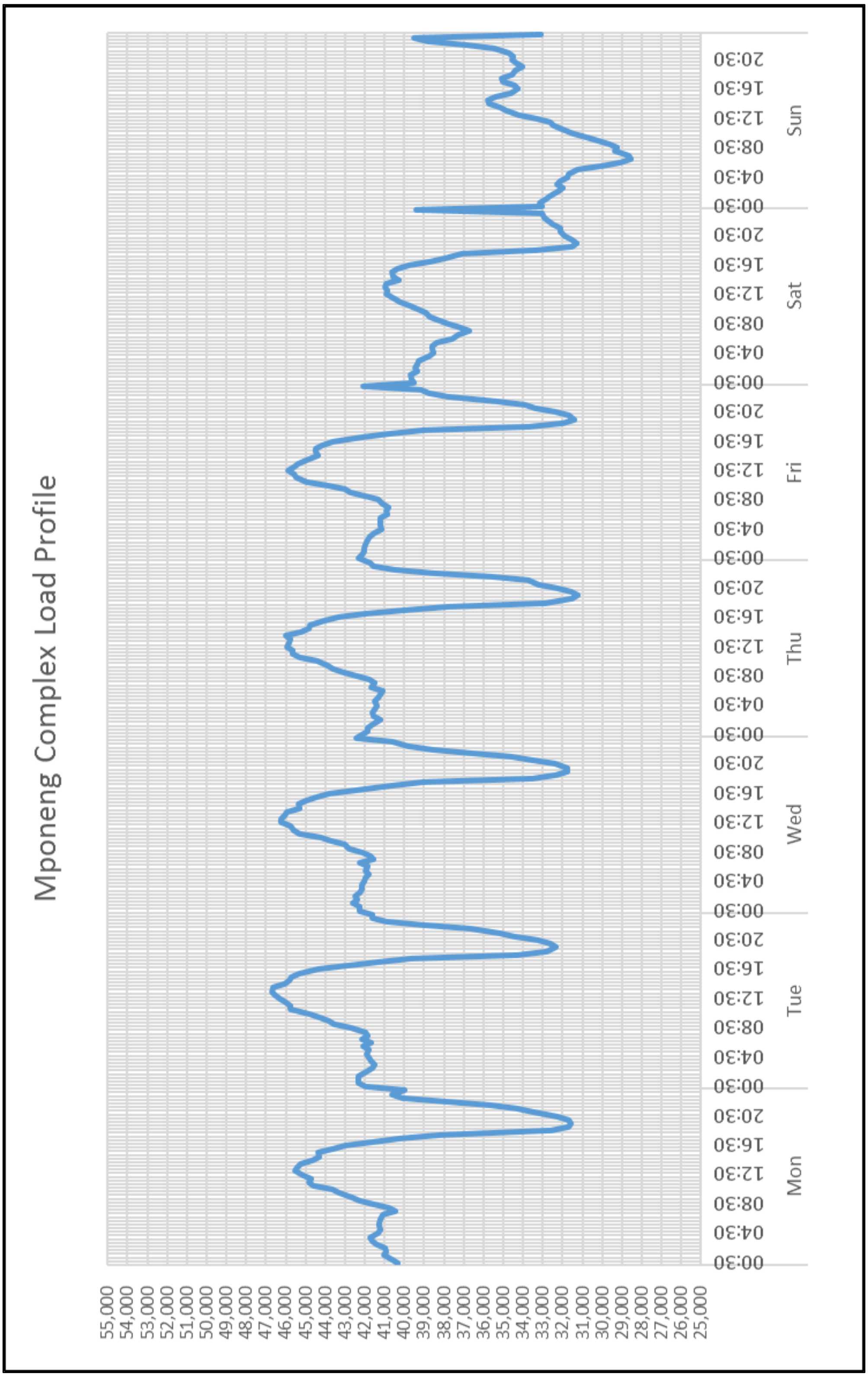
https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&cad=rja&uact=8&ved=0ahUKEwjOifGYhN_WAhVIJ8AKHR1SDgsQFghJMAQ&url=http%3A%2F%2Fwww.ewp.rpi.edu%2Fhartford%2F~ernesto%2FS2014%2FET%2FMaterialsforStudents%2FTweedie%2FZouo2012-SOFC.pdf&usg=AOvVaw. Accessed: 23 September 2017

Appendix I – Mponeng Complex Load Profile (AngloGold Ashanti Limited, 2016a)



Appendix II – Mine Waste Solutions Load Profile (AngloGold Ashanti Limited, 2016b)