DEVELOPING A FUEL CELL INDUSTRY IN SOUTH AFRICA: A TRIPLE-HELIX ANALYSIS

by

Franca Peverelle

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Supervisor: Dr. Andre Kraak

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ABSTRACT

Globally, the concept "knowledge economy" has evolved as the dominant economic logic that is premised on the importance of new knowledge for innovation and competitiveness, and on the sharing of that knowledge through various forms of knowledge transfer based on collaboration. This is the context of this study, which focuses on how knowledge transfer and the relationship between university, industry and government impact the development of the fuel cell industry in South Africa as informed by the triple-helix systems theory.

From the literature it is evident that the beneficiation potential of South Africa is a top development priority for policymakers with a view to boosting the country's economic potential. Furthermore, South Africa is reportedly not leveraging its natural platinum resources effectively, resulting in high levels of raw-platinum exportation and high levels of platinum product imports. The problem statement thus suggests that supporting and developing a local fuel cell industry in South Africa through active partnerships between universities, industry and government may contribute to a reduction in the amount of raw platinum being exported, exploiting the platinum reserves for heightened South African economic development.

This is a qualitative case study comprising semi-structured interviews based on the selection of participants through purposive and snowball sampling techniques. The Hydrogen South Africa programme, a large player in the South African fuel cell industry, has partnered with three South African universities, namely North-West University, University of Cape Town and Western Cape University, to develop various elements of hydrogen fuel cells, providing a key opportunity for a case study on the current relationship between university, industry and government in the fuel cell industry.

The triple-helix system depicts the importance of the roles played by universities, industry and government as well as the importance of collaboration among them. Overall, this study aims to demonstrate the potential power of the triple-helix system to allow for the development of a globally competitive local fuel cell industry that may reduce the exportation of platinum resources for beneficiation purposes, rather utilising the potential within South Africa.

This study will firstly explore the role of higher education institutions in supporting the development of the required skills for the fuel cell industry through relevant research and development projects that may result in fuel cell technology innovations and commercialisation opportunities. Secondly, the study will seek to demonstrate industry's role in continuously advancing workers' skills through training and active knowledge transfer in collaboration with universities, as well as b eing involved with research and

development projects at universities and research institutes with the aim of developing the fuel cell industry. The study will thirdly seek to document government's role in providing support and guidance in the form of policy development and funding for research initiatives in the science and technology innovation space, as well as its role as mediator between the education and industrial sectors.

DECLARATION

I, Franca Peverelle (Student number 1016694), declare that this thesis titled “**Developing a Fuel Cell Industry in South Africa: A triple-helix analysis**”, is my own, unaided work. It is being submitted for the Degree of Master of Education (M. Ed.) from the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

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Franca Peverelle

Signed at____ on ___________________________

Place Date

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ACRONYMS AND ABBREVIATIONS

AFC	alkaline fuel cell
AMCU	Mineworkers And Construction Union
AMPLATS	Anglo American Platinum Limited
AMTS	manufacturing technology strategy
ASSAF	Academy of Science of South Africa
BRPM JV	Bafokeng Rasimone Platinum Mine Joint Venture
CEI	clean energy investments
CFCL	Ceramic Fuel Cells Limited
CHP	combined heat and power
CoC	centre of competence
CSIR	Council for Scientific and Industrial Research
COSATU	Congress of South Africa Trade Unions
DFC	directional flow control system
DHET	Department of Higher Education And Training
DMFC	direct methanol fuel cell
DMR	Department of Mineral Resources
U.S.DoE	United States Department of Energy
DST	Department Of Science And Technology
dti	Department of Trade And Industry
EERE	energy efficiency and renewable energy
EV	electric vehicle
FCES	fuel cell energy solution(s)
FCEV	fuel cell electric vehicle
FCH JU	fuel cells and hydrogen joint undertaking
FCTO	Fuel Cell Technologies Office
GDP	gross domestic product
GFC	global financial crisis
H_2	molecular hydrogen
HEI	higher education institutions
HFCT	hydrogen fuel cell technologies
HT-PEM	high-temperature proton exchange membrane
HySA	Hydrogen South Africa
ICT(s)	information and communication technology/technologies
IDC	Industrial Development Corporation
IMPLATS	Impala Platinum Limited
IPAP	Industrial Policy Action Plan
JOBSFC	job and output benefits of stationary fuel cells
KBE	knowledge-based economy
KW	kilowatt
MCFC	molten carbonate fuel cell
MEA	membrane electrode assembly
merSETA	Manufacturing, Engineering and Related Services Seta
MPRDA	Mineral And Petroleum Resources Development Act, 49 of 2008
NCAP	national career advice portal
NDP	National Development Plan
NEDO	New Energy And Industrial Technology Development Organisation
NEED	National Energy Education Development
NGP	National Growth Plan
NIP	National Innovation Programme
NOW GmbH	National Organisation Hydrogen and Fuel Cell Technology (Germany)
NRF	National Research Foundation
NSDS	National Skills Development Strategy
NTER	national training and education resource
NWU	North-West University
O_2	oxygen

OECD	Organisation for Economic Co-operation and Development
P2G	power-to-gas
PAFC	phosphoric acid fuel cell
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
PGMS	platinum group metals
PhD	Doctor of Philosophy
POSCO	leading energy producer in South Korea
PTSI	powertech system integrators
R&D	research and development
RD&D	research, development and demonstration
SCIR	Council For Scientific and Industrial Research
SEP	Strategic Energy Plan
SETA	Sectors Education and Training Authority
SME	small and medium-sized enterprise
SOFC	solid oxide fuel cell
SSP	Sectors Skills Plan
STEM	science, technology, engineering and mathematics
STI	science, technology and innovation
TECH4RED	technology for rural education and development
U.S.	United States
UCT	University of Cape Town
UNISA	University of South Africa
UPS	uninterruptible power supplies
UWC	University of Western Cape

SECTION A: BACKGROUND AND CONCEPT

CHAPTER 1: INTRODUCTION AND METHOD

This chapter serves as an introduction to this thesis, providing the background context for the study and placing the fuel cell industry as an emerging subsector within the wider South African manufacturing sector. South Africa is underutilising its platinum resources. Therefore, to create a sustainable demand for platinum group metals, increase exportation of final products and limit imports, new industries that utilise platinum need to be identified. For this thesis the fuel cell industry was identified as such an industry. To develop such a high-tech industry in South Africa requires knowledge transfer and sharing between the triple-helix spheres, namely universities, industry and government, which is the main argument of this thesis. In essence, the primary focus of this thesis is employing the triple-helix model as a guide for the possible development of a local fuel cell industry in South Africa and, although not focusing on the manufacturing of fuel cells or platinum beneficiation required for fuel cell development directly, this forms the background context of the study.

Therefore, the South African manufacturing sector, and more specifically the platinum sector and its links to the fuel cell industry, needs to be understood before looking at the possibility of developing a local fuel cell industry in the country through a triple-helix collaboration. The chapter concludes with a discussion of the research problem, objectives and focus, and followed by the literature review in the subsequent chapter.

1.1 Contextual background

South Africa is currently on a low economic growth path with a declining manufacturing sector, in terms of both its contribution to economic growth and employment. The patents issued in South Africa are also exceptionally low in number and seem to be concentrated in the mining sector (Bhorat and Rooney, 2016: 1; Doke, 2015: 1). The South African economy is directly influenced by global developments, which ultimately have a negative effect on the country’s manufacturing industry. In addition, the complex and volatile global economy creates economic uncertainty (IPAP, 2017: 4). An indication of these spillover effects is the slow global recovery following the 2008 global financial crisis (GFC) (IPAP, 2017: 18; Buchanan, 2016: 5; merSETA SSP, 2016: II). The South African manufacturing sector is also subjected to high volatility due to the economic and political climate, as well as structural changes within the manufacturing sector. It is anticipated that economic growth will remain relatively weak owing to policy and political uncertainties as well as an adverse external context (merSETA SSP, 2016: 53).

According to the South African Minister of Trade and Industry, due to structural changes – particularly in China, there is a sharp reduction in the demand for mineral commodities, resulting in a sharp contraction in their growth rates in South Africa and other countries on the African continent (RSA, 2016: 1). For South Africa as an emerging market and platinum-rich country, the impact of the decline in demand and price of key minerals has been severe, resulting in immense pressure on the economy and business confidence in manufacturing (RSA, 2016: 1). This is another example of the direct effects of global developments on the country. The South African export sector came under increased pressure in 2014 due to falling commodity prices, production stoppages due to labour strikes in the platinum mining industry, reduced global demand and production challenges experienced by key export-oriented manufacturing sectors (IPAP, 2017: 21).

Global trading conditions, with adverse "home-grown factors [further] aggravating the manufacturing sector's performance and the harsh recessionary conditions in the Eurozone have damaging effects on the local manufacturing sector, specifically its export-oriented segments" (merSETA SSP, 2016: 14). The sector is facing rising imports and declining exports of some manufactured products, resulting in a struggling manufacturing sector (merSETA SSP, 2016: 54).

Additional factors that constrain the South African manufacturing sector's performance include increasing production and wage costs; a shrinking manufacturing base; supply chain challenges; the threat of other emerging economies that continue to threaten the growth of local South African manufacturers; high levels of inequality and unemployment; skills shortages and mismatches; inadequate and overstrained infrastructure; operational bottlenecks; overconcentration in key sectors of the economy; conflicting industrial relations; inequitable spatial patterns; extensive cost pressures; unstable supply and high cost of electricity; exchange rate volatility; high administered prices and industrial relations that are intensified by productivity and competitiveness challenges; the lack of long-term investments in the manufacturing sector; persistent illegal imports and customs fraud; slowdown in manufacturing research and development (R&D), as well as technology acquisition; intragovernmental programme and regulatory bottlenecks; operational problems and non-compliance with key policy levers as well as monopoly pricing (IPAP, 2017: 27; Bhorat, 2016: 1).

Amid the growing global economic uncertainty and volatility, it has become increasingly evident that it is important for South Africa to industrialise, diversify and break its dependence on exporting its raw resources, rather focusing on utilising natural resources more effectively by beneficiating locally and increasing exports (Crosby, et al., 2016: 1; Bhorat, 2016: 1). This may provide the country with an opportunity to develop a local fuel cell industry through utilising (beneficiation and manufacturing) its platinum resources, supported by active triple-helix dynamics between universities, industry and government.

Factors in favour of South Africa's undertaking local mineral beneficiation include the fact that the country has a natural monopoly on certain mineral reserves such as platinum, that the country has a competitive advantage in some mining and smelting activities, that it has experience in the beneficiation of certain minerals at firm level and that it is supported by government as an economic enabler (Soko and Balchin, 2012: 9; Erasmus, 2013; Manda and Crosby, 2016: 1). Utilising the platinum reserves for local platinum beneficiation and fuel cell manufacturing may facilitate the reduction in imported goods and increase product exports, thereby growing a stronger manufacturing sector for the country. Growing the South African manufacturing sector lies in beneficiation as well as advanced manufacturing, which require investment in those capabilities mostly associated with high-level skills, such as innovation and R&D to ensure global competitiveness (Manda and Crosby, 2016: 1).

Furthermore, high-value-added manufacturing (beneficiation) has been identified by government as an important mechanism to further diversify the South African economy and this will require focused efforts (partnerships) from various entities (merSETA SSP, 2016: 55). It seems clear that, in developing any local high-tech industry, the role of partnerships, especially between universities, industry and government as highlighted in the triple-helix model, cannot be overemphasised and more R&D in areas of sector growth should be facilitated (merSETA SSP, 2016: 56).

Because of the high-level skills required for innovation and research in high-tech industries such as the fuel cell industry, there needs to be a stronger focus on science, technology, engineering and mathematics, also referred to as STEM (Manda and Crosby, 2016: 1). This underlines the importance of the triple-helix dynamics of university, industry and government partnerships to enable innovation and research. Funding would typically be required from government, research experts in the STEM fields from universities would be required for R&D activities, and field locations linked to industry would be required for the implementation of innovations.

The applicability of triple-helix dynamics is further verified by Manda and Crosby (2016: 1), stating that the future of the South African manufacturing sector relies on successful collaborations between large and small as well as private and public stakeholders, which emphasises the importance of partnerships between government, industry and higher-education institutions (HEIs) in restoring the manufacturing sector. Manufacturing needs to be a key focus as it has the capacity to uplift an economy due to its ability to add value and create jobs, and if the country's manufacturing sector is to be revived, there needs to be a substantial refocus and collaboration between government, business and education for the sector's progress (Doke, 2015: 1).

1.1.1 Government support for fuel cells

Government has various critical roles in facilitating enabling policy and legislative frameworks that provide an attractive environment for business operations and investment in the country. These typically include providing funding for key research initiatives around new technologies and acting as an intermediary between industry and university players as argued in the triple-helix model.

The Industrial Policy Action Plan (IPAP) of the Department of Trade and Industry (dti) can be considered as one of the key policy initiatives aimed at stimulating economic growth focused on shifting towards a more diversified knowledge economy (Crosby et al., 2016: 1). The recent iteration of the IPAP touches on the development of the science and technology field, the importance of the Green Economy, the development of a fuel cell industry and the importance of collaboration. The document highlights the vital role of science, technology and innovation (STI) in economic growth, which is a major source of competitive advantage providing it is properly coordinated and has the capacity to absorb and quickly adapt to new forms of knowledge and technical capabilities (IPAP, 2017: 73). For knowledge-intensive programmes such as fuel cell initiatives, efforts are being made to create enabling environments to improve the coordination of technology development and commercialisation initiatives across the public sector in order to fast-track the commercialisation of such innovative technologies (IPAP, 2017: 79).

The IPAP highlights the need for a better mix of public and private sector funding to support diversification in the manufacturing sector and increase the sector's ability to absorb, adopt and commercialise new technologies (IPAP, 2017: 49). Government is urgently trying to build a stronger system of industrial finance and incentives to support sectors of the economy where the country has globally competitive industrial capabilities such as the fuel cell industry (IPAP, 2017: 6). The need for stronger support for the manufacturing sector is emphasized, with specific focus on supporting the competitiveness and sustainability of labour-absorbing sectors and subsectors, as well as the export of South African goods (IPAP, 2017: 48). Strategically, the country requires a massive industrial effort, which according to the IPAP needs to be based on policy coherence and policy certainty across government; close collaborative efforts between government, business and labour; commitment to ensure that the linkages between the primary and secondary productive sectors of the economy are maximised; and a combined and constructive drive to overcome the key constraints to manufacturing, highlighting the importance of partnerships (IPAP, 2017: 50).

The IPAP highlights the advancement of beneficiation where material measurement, referring to the characterisation and compositional analysis of metals, is key for increased beneficiation and advanced manufacturing (IPAP, 2017: 56). The production and exportation of primary minerals as mentioned have been difficult due to the volatile global economic environment and the crash in commodity prices mainly due to overcapacity and reduced demand. As this has a negative effect on mineral commodities produced in the country, there is an urgent need for value addition as well as new uses for the country's natural resources such as platinum (IPAP, 2017: 60). Fuel cell technology has been highlighted as a possible solution due to its high dependency on platinum, which is produced in South Africa. According to the IPAP, developing a local fuel cell industry may offer growth opportunities for the platinum mining industry, ensuring a sustainable platinum industry in South Africa. Additionally, it may generate and support broader industrial development in the country and spread platinum-based value addition to other key manufacturing sectors (IPAP, 2017: 150). However, for this to be achieved a deliberate and focused approach is required, which should typically include partnerships between government and industry, such as local engineering and manufacturing companies, which are key for platinum-based re-industrialisation in South Africa (IPAP, 2017: 150). Thus, the document acknowledges that considerable progress in the fuel cell industry is being made through collaborations between government and industry stakeholders (IPAP, 2017: 56). The Green Economy is also discussed in the IPAP, focusing on the shift away from the conventional diesel- and petrol-driven road transport industry, paving the way for greener technologies such as fuel cells (IPAP, 2017: 46).

The National Development Plan (NDP) was commissioned by the South African President in 2010 as a broad strategic framework to guide key choices and actions of the country. The document states that the country needs to expand its science, technology and innovation outputs through increasing R&D spending by government as well as industry, which is indicative of the necessity of triple-helix dynamics (NDP, 2013: 60). It is crucial for a middle-income country such as South Africa to use its knowledge and innovative products to compete on a global scale as innovation is necessary for such countries to develop (NDP, 2013: 60). It is also highlighted that the institutional setup needs restructuring, with an improved link between innovation and business requirements, and government partnering with the private sector to raise the level of R&D (NDP, 2013: 40). In essence, the NDP argues for greater investment in R&D, better use of existing resources and more institutions able to facilitate innovation and enhanced cooperation between public science and technology institutions and the private sector, linking to the triple-helix model (NDP, 2013: 23).

The New Growth Path (NGP) is a framework for placing decent jobs and work at the centre of economic policy, with a target of five million new jobs to be created by 2020. The document highlights the mining sector, the manufacturing sector, the Green Economy and the knowledge economy as key sectors for job creation and economic growth, also argued in this thesis. The areas emphasised by the framework are increasing platinum exports; increasing final manufactured products that use base metal products; accelerating the exploitation of reserves through measures that support the beneficiation strategy and fabrication rather than only smelting and refining, which are both capital and energy intensive; and addressing uncompetitive pricing of intermediate inputs (NGP, 2011: 72). For the manufacturing sector the aim is to create 350 000 jobs by 2020, which requires support for manufacturing activities that encourage employment on a large scale and are able to lower cost in the short to medium term and sustain the development of knowledge-intensive industries for the long-term (NGP, 2011: 72). The framework also emphasises the need for a greater output of relevant skills such as engineers, designers and artisans for the manufacturing sector in South Africa (NGP, 2011: 72).

The Green Economy has also received attention in the NGP, with an aim of creating an additional 300 000 direct jobs by 2020, of which 80 000 will be in manufacturing and the rest in construction, operations and maintenance, and with a further aim of exceeding 400 000 jobs by 2030 (NGP, 2011: 74). Attempting to embrace the new knowledge-based economy, the NGP highlights aims to create 100 000 jobs by 2020 in knowledge-intensive fields such as public services, information communication technology (ICT), higher education, healthcare, "green" technologies and mining-related technologies among others (NGP, 2011: 74). These knowledge-intensive industries directly link to technical innovations, which increasingly create employment opportunities based on the country's ability to emulate, adapt and diffuse existing technologies from abroad (NGP, 2011: 74). What is required is increased R&D support and tertiary education, growing exports in knowledge-based services and production technology and skills policy (NGP, 2011: 74).

The Department of Science and Technology (DST) acknowledges that platinum-based fuel cells could stimulate demand for platinum and provide a platform for local beneficiation of platinum group metals, and a number of activities are therefore currently being undertaken by government and industry to develop a local market for hydrogen fuel cells in the country (DST APP, 2017: 31). The local fuel cell landscape has been assessed by a multi-stakeholder forum on mining, which highlighted that the local market potential is limited and requires a global focus. The forum stated that, currently, South Africa does not have the infrastructure critical to support the local deployment of fuel cells, and that South Africa should prioritise mining vehicles, commercial and industrial combined heat and power (CHP), and off-grid power in the short-term (DST APP, 2017: 32). With the adoption of government's nine-point plan to diversify and enhance the competitiveness of the South African economy, the DST is to review their R&D-led industrial development interventions to ensure its alignment to the plan. As such, the DST continues to support the expansion of the additive manufacturing industry, with a specific focus on opportunities in metals such as platinum (DST APP, 2017: 32). A key focus is hydrogen and energy to facilitate increased local mineral beneficiation, and facilitation of South Africa's transition towards a knowledge-driven economy (DST APP, 2017: 61).

Regarding the DST's Hydrogen South Africa (HySA) programme, the department will ensure that the centres of competence (CoCs) leverage each other's strengths to support the Department of Trade and Industry-led national fuel cell task team. It is also indicated that work supported by the Council for Scientific and Industrial Research (CSIR) and the Technology Innovation Agency will promote the integration of local technologies into the Renewable Energy Independent Power Producer Procurement Programme and Biofuels Industrial Strategy (DST APP, 2017: 56). Additionally, emphasis is placed on moving the HySA programme from an R&D initiative to a manufacturing initiative through the HySA hydrogen fuel cell deployment plan and deploying HySA technologies in niche markets in South Africa, in line with government's programme of action commitment to deploy 25 hydrogen fuel cell technologies (HFCT) by 2020 (DST APP, 2017: 4). The HySA programme office, established in 2016, will commercialise the technologies and the fuel cell task team will be revived to improve coordination across government, private industry and universities (DST APP, 2017: 5). This will require financial commitments from the private sector and other government departments, with the department having raised almost R40 million in support of the 2020 target for hydrogen fuel cell technologies (DST Budget Vote, 2017: 1).

The DST's programme 5, named "Socio-economic Innovation Partnerships", aims to enhance growth and development priorities of government through targeted science- and technology-based innovation interventions as well as developing strategic partnerships with other government departments, industry, research institutions and communities (DST APP, 2017: 116). Some focus areas of this programme include advanced manufacturing, resource-based industries and environmental technologies, and has since 2015 supported 668 students in these priority areas at honours, master's and Doctor of Philosophy (PhD) levels (DST APP, 2017: 117).

The Beneficiation Strategy of the Department of Mineral Resources (DMR) was adopted by the South African Cabinet in 2011 based on recognition of the fact that South Africa has low levels of mineral beneficiation and most of the country's minerals are exported as ores and semi-processed minerals as opposed to high-value intermediate to finished products (DMR, 2014: 42; DMR, 2011: iii). The strategy aims to provide a strategic focus for the country's minerals through developing mineral value chains and facilitating the expansion of beneficiation initiatives, and unlocking downstream and side-stream beneficiation linkages (DMR, 2011: 1). Additionally, the strategy seeks to increase a ratio of beneficiation extent to mineral production; to increase export revenue; to enhance the country's productivity; to facilitate economic diversification; to advance progress towards technology development and a knowledge-based economy; to create opportunities for new enterprise development; to contribute to decent job creation; to alleviate poverty; and to attain incremental gross domestic product (GDP) growth per capita in mineral value addition (DMR, 2014: 32; DMR, 2011: V). The Department of Mineral Resources (DMR) would need to encourage strong links into manufacturing partnerships and coordination, which at this point does not seem to be the case.

It has been stated that the implementation of beneficiation policies has thus far been relatively unsuccessful, with mineral beneficiation remaining an untapped opportunity for the country (merSETA SSP, 2016). As part of IPAP 2013/14 to 2015/16, government has committed to undertaking comprehensive research that will support the development of a strategy and action plan to advance backward and forward beneficiation in a selected group of key minerals value chains that include platinum group metals (PGMs) (merSETA SSP, 2016: 54).

1.1.2 University support for fuel cells

The role of higher education and training institutions in facilitating skills development for the manufacturing industry is vital to provide the skills required to drive re-industrialisation as well as to undertake relevant R&D development projects applicable to industry, thereby assuming an entrepreneurial role in society. More specifically, in relation to the novel and growing fuel cell industry in South Africa, critical skills required for the beginning stages of the industry are limited to high-level STEM skills such as engineering, chemistry and high-level R&D (IDC, 2013: 20; HySA PADEP, 2015: 23). Therefore, universities need to focus on increasing the output of STEM-related qualifications, preferable at master's and PhD level. The fulfilment of this role may enable the country to establish a much needed, stable and innovative base that can consistently support developments in high-science and technology fields such as the fuel cell industry so that the country can reap success locally and globally.

Currently, innovation policy mechanisms mainly focus on universities' responsiveness to economic needs and the promotion of global competitiveness, while higher-education policy focuses more on universities' responsiveness to issues of social justice and promoting the interests of the public (Kruss, 2010: 6). The National Research Foundation (NRF), South Africa's principal agency that supports and promotes research through funding, human capital development and provision of research equipment facilities, is closely aligned to the higher-education mandate of research (Mouton and Gevers, 2009: 48). Additionally, all public HEIs are also funded by the Department of Higher Education and Training (DHET) through a complex formula that takes into account both teaching loads and research activity and includes field-specific factors and a variety of developmental parameters (Mouton and Gevers, 2009: 45).

As HFCT is a highly-specialised research field, it requires high-level skills and extensive R&D initiatives at master's and PhD levels to innovate and improve the industry continuously. Skills that need to be developed around this initiative generally fall within the STEM domain; however, in South Africa there seems to be a general concern about performance in STEM (Kaniki and Steele, 2012: 6; Crosby et al., 2016: 1). School-level mathematics and science are essential for completing an engineering degree at university, which opens doors into the fuel cell industry. As research in this fields requires a broad spectrum of disciplines, any science degree, typically including physics and chemistry, applied materials chemistry, chemical or mechanical engineering, electrical engineering, electronics or metallurgy, is adequate (HySA PADEP, 2015: 23). After completing a science degree in the fields highlighted above, an honours degree in engineering or science is required to be eligible to complete a master's or PhD degree in the fuel cell technology field (HySA PADEP, 2015: 23).

Several South African universities and science councils are currently engaged in research on HFCT, most of them falling within the HySA framework and linked to the HySA CoCs. As will be mentioned in the section on HySA Systems in Chapter 5, these participants include University of the Western Cape (UWC) the research group of which has been involved in HFCT R&D since the mid-1990s and holds several related local and international patents, the University of Cape Town (UCT) and North-West University (NWU) (HySA PADEP, 2015: 24).Other South African universities that also have collaborative agreements with these CoCs and are also involved in R&D programmes that advance knowledge generation in HFCT include University of the Witwatersrand, University of Johannesburg, University of Limpopo, Tshwane University of Technology, Nelson Mandela Metropolitan University and Stellenbosch University (HySA PADEP, 2015: 24). The University of the Witwatersrand is active in advancing the use of hydrogen materials in fuel cells and energy storage (Msimang, 2014: 146). Technologies such as fuel cell membranes, batteries and heat transfer media are some areas in which progress has been made at the university (Msimang, 2014: 146).

A report released by the Academy of Science of South Africa (ASSAF) in 2014 indicated that, during the period 2006 to 2013, both Stellenbosch University and University of Johannesburg contributed 15% of completed master's and PhD degrees in and related to energy, University of the Witwatersrand contributed 7%, Tshwane University of Technology and Nelson Mandela Metropolitan University both contributed 5%, while University of Limpopo contributed 3% (ASSAF, 2014: 107). When comparing the seven main HEIs, namely University of the Witwatersrand, Tshwane University of Technology, Nelson Mandela Metropolitan University, Stellenbosch University, UCT, UWC and University of Pretoria, with other HEIs, they contributed a total of 75% completed master's and doctoral degrees related to energy in the period 2006 to 2013 (ASSAF, 2014: 107). For the same period 43% of the master's and doctoral output was related directly to renewable energy, nuclear energy and energy from fossil fuels, with 57% of the output attributable to storage, hydrogen and fuel cells (ASSAF, 2014: 107).

Globally, there is a move towards expanding universities' mission to interact more closely with industry and to build connections between firms and universities with the objective of promoting innovation and economic development (Kruss, 2010: 2). Initially, the entrepreneurial university was a phenomenon mostly in developed countries, but has since the 1990s spilled over into developing countries such as South Africa (Kruss, 2010: 2). However, due to the high levels of inequality and human development challenges in such countries, the applicability of the entrepreneurial models adopted by dominant countries is limited (Kruss, 2010: 2). This leads to developing countries re-conceptualising the changing roles and missions of the university, and to come up with ways universities can leverage their knowledge resources (Kruss, 2010: 2). This causes a change in the nature of academic roles, and the impact of a perceived shift from basic to applied research on future knowledge generation, as influenced by the global debate around Mode 1 and Mode 2 forms of knowledge production (Kruss, 2010: 7), will be discussed in Chapter 3.

The White Paper on Science and Technology (1996) identified strategic alliances, networks, partnerships and collaboration between universities and industry as a primary means of repositioning higher education to play a new role in economic development (Kruss, 2010: 6). The DST established funding and incentive mechanisms as well as new institutions to drive university–industry interaction aimed at addressing the technology achievement problems evident in South Africa, indicative of triple-helix dynamics (Kruss, 2010: 6). These incentives typically include government and industry research co-funding programmes, innovation incentivisation funding programmes, sectoral incubators and technology platforms (Kruss, 2010: 6).

South African policy mechanisms were strongly influenced by the U.S. model for the promotion of technological transfer, commercialisation and incubation in high-technology fields such as fuel cells (Kruss, 2010: 6). In 2008 new legislation endorsed the utilisation and commercialisation of intellectual property developed from publicly funded research for social and economic benefit, as well as a centralised coordination agency to stimulate and intensify technological innovation (Kruss, 2010: 6). Universities became pressured to exploit feasible knowledge technology developed through academic research as well as focus on transfer offices at universities (Kruss, 2010: 7).

Kruss (2010: 10) states that it seems that, although research universities are strongly committed to new national goals, they are struggling with the development of adequate policy structures and the organisational forms required to enhance interactive capabilities. Universities are currently not sufficiently coordinating and aligning their research, teaching and outreach operational structures, which require clear conceptualisations for success. Universities have not coordinated and aligned the interface mechanisms that support and facilitate external partnerships to promote new opportunities for social and firm innovation (Kruss, 2010: 10).

1.1.3 Industry support for fuel cells

According to the triple-helix model, the role of industry is to provide skills training to employees on a continuous basis, to conduct research and to transfer knowledge with university and research institutes. Although the South African fuel cell industry (still at an R&D stage) is rather small, with limited demand, the industry is steadily gaining interest, especially due to its environmental benefits. There are various emergent partnerships around fuel cell technology in South Africa, with a leading example of a triple-helix collaboration being the HySA initiative. This programme is a partnership between various universities, industry players as well as the DST, who work together to further the fuel cell industry. As the HySA initiative is the main focus of this study, falling within the fuel cell industry context, it is discussed in depth in Chapter 5.

1.2 Problem statement, objective and focus

Globally, the concept "knowledge economy" has evolved as the dominant economic logic that is premised on the importance of new knowledge for innovation and competitiveness, and on the sharing of that knowledge through various forms of knowledge transfer based on collaboration. This is the context of this study, which focuses on how knowledge transfer and the relationship between university, industry and government impact the development of the fuel cell industry in South Africa, as informed by the triple-helix theory.

The literature suggests that the beneficiation potential of South Africa is a key focus for policymakers to boost the country's economic potential. Furthermore, South Africa is reportedly not leveraging its natural platinum resources effectively, resulting in high levels of raw platinum exportation and high levels of platinum product imports. As fuel cells require elements of platinum, the problem statement therefore suggests that supporting and developing a local fuel cell industry in South Africa through active triple-helix relationships or active partnerships between universities, industry and government may contribute to reducing the amount of raw platinum being exported and to exploiting the platinum reserves locally for heightened South African economic development. Based on this problem statement, and the importance of triple-helix dynamics in the fuel cell industry, this study seeks to explore the extent to which triple-helix relationships are taking place in the current South African fuel cell industry.

As the HySA programme was initiated by the DST to further the fuel cell industry by developing three CoCs, namely HySA Infrastructure, HySA Catalysis and HySA Systems, all based at separate universities, it was identified as key player in the current fuel cell industry where triple-helix dynamics occur. As such, HySA was selected as a case study for this thesis to explore the extent of triple-helix relationships in the current fuel cell industry.

1.3 Research questions

From the research problem emphasised above, the following research questions were developed:

- To what extent are triple-helix dynamics taking place in the fuel cell industry/context in South Africa?
- Who are the main players on the side of university, industry and government in the fuel cell industry?
- What advantages and challenges have presented themselves through these triple-helix partnerships?

1.4 Summary

As South Africa is the largest global platinum producer in the world (a key component in fuel cells), the country may have the opportunity to develop a sustainable and competitive local fuel cell industry through strong triple-helix dynamics. The triple-helix model depicts the importance of the roles played by university, industry and government as well as the importance of collaboration between them for the purpose of knowledge transfer. The overall aim of this study is therefore to demonstrate the potential power of triple-helix dynamics to allow for the development of a local, globally competitive fuel cell industry that may reduce the exportation of platinum resources in favour of utilising its potential within South African borders. Ideally, universities should provide high-level education and training relevant to industry and conduct research around fuel cell technology; industry should provide skills training to employees on a continuous basis, conduct research in the fuel cell field as well as transfer/exchange knowledge to/with university and research institutes; government should provide support in the form of funding for research initiatives at institutional or company level in the science and technology innovation space, embark on policy development and act as mediator between the education and industrial sectors.

The chapter provided some insight into the support provided by universities and government for the fuel cell industry in South Africa. The fuel cell industry requires high-level skills and extensive R&D activities at master's and PhD levels, mostly falling within the STEM domain. Numerous South African universities and science councils are engaged in fuel cell technology development, as identified in the section above. Government seems to be aware of the need to move towards a knowledge-based economy and the policies discussed talk to the increasing need for science- and technology-based innovations (STEM skills), the adoption of green processes and technologies for the Green Economy, the need to develop new uses for the country's natural resources, and the advancement of local beneficiation of primary minerals such as platinum as well as the exportation thereof. It needs to be noted at this stage that although fuel cells are classified as a green technology, this thesis focuses on the manufacturing advancement of the technology. The importance of collaborative efforts/strategic partnerships between government departments, industry, research institutions and universities (triple-helix dynamics) is also highlighted.

CHAPTER 2: METHODOLOGY

This chapter outlines the methodology and research instruments used in the study. The study made use of a combination of literature review and the document research method for gathering information prior to entering the field. The study consists of three small site studies, for which participants were selected through purposive sampling and information gathered by means of semi-structured interviews. These methodologies and methods are all elaborated on below.

2.1 Methodology

This section provides insight into the methodology used to source the information covered in the literature review, which is critical for understanding how and on what basis the research focus and research questions were established. The section will also highlight the methods used for data collection, as well as how these methods and participants were selected. Research methodology is understood as a strategy that demonstrates how research should be constructed and conducted through turning ontological and epistemological principles into guidelines (Sarantakos, 2013: 29). In short, ontology deals with the nature of reality and assumptions of the world, while epistemology deals with the nature of knowledge and assumptions about the best way to study the world, producing knowledge through research (Sarantakos, 2013: 28; Bhattacherjee, 2012: 18). Methodology, which is closely linked to these concepts, refers to the nature of the research design and methods, which is guided by the ontological and epistemological assumptions made by the researcher (Sarantakos, 2013: 28; Bhattacherjee, 2012: 18).

2.2 Literature review and documentary research

This study is primarily concerned with uncovering the dynamics and level of knowledge transfer (a key part of triple-helix engagements/dynamics) occurring between entities of the triple-helix model (university, industry and government) within the South African fuel cell industry. As fuel cell technology utilises platinum resources, the South African platinum mining industry should also be considered. Thus, the literature methodology used was twofold. On the one hand, as the South African mining and platinum industry has a long history in the country, extensive sources were available to ensure an informed literature review on this topic, which forms the basis for the fuel cell industry. On the other hand, as the fuel cell industry is still in the early stages of development globally and mostly at a research and development (R&D) level in South Africa, there was limited information and literature in the primary sources available on this field. Therefore, the study also utilised the document research methodology to ensure relevant information is used to guide the study focus and research questions.

The documentary research method is the analysis of documents containing information on the phenomenon to be studied, which are referred to as primary and secondary documents (Mogalakwe, 2006: 222). Primary documents refer to documents produced by people who have experienced, first-hand, the particular event or context to be studied (Mogalakwe, 2006: 223; McCulloch, 2004: 25). Secondary documents are produced by those who were not physically present at an event, but base their documents on eye-witness accounts they have received or read (Mogalakwe, 2006: 223; McCulloch, 2004: 25).

When using the documentary research method, it is vital to have quality control measures in place. These typically include issues of authenticity, credibility, representativeness and meaning (Mogalakwe, 2006: 225). The authenticity of documents relates to whether the evidence presented is genuine, and from impeccable sources with a dependable origin (Mogalakwe, 2006: 225; McCulloch, 2004: 91). The credibility of documents relates to whether the evidence is typical of its kind as well as free from error and distortion. The representativeness of documents relates to whether the documents are representative of the totality of the relevant documents (Mogalakwe, 2006: 226; McCulloch, 2004: 69), and finally meaning relates to whether evidence presented is clear and comprehensible (Mogalakwe, 2006: 227).

From the literature review and document research on the fuel cell industry in South Africa, the Hydrogen South Africa (HySA) initiative was identified as a possible focus for this study. This was based on the fact that the initiative was established by the DST, as representative of government, that it was rolled out at universities in the form of Centres of Competence (CoCs) focusing on different fuel cell elements, and that partnerships existed with various industry players. Through a combination of literature review and document research, collaboration between these players was identified, clearly indicating that triple-helix dynamics are present within the South African fuel cell industry context. These CoCs were therefore selected as suitable cases to study.

2.2.1 Qualitative case studies

As mentioned above, the HySA initiative is a key player in the South African fuel cell industry, specifically around R&D activities, and was therefore selected as the main focus for this study. The HySA comprises three CoCs based at and hosted by three universities, namely HySA Infrastructure hosted by North West University (NWU), HySA Catalysis hosted by the University of Cape Town (UCT) and HySA Systems hosted by the University of Western Cape (UWC).

These three CoCs, with their indicated university, industry and government partnerships (triple-helix relationship), were identified as three small site studies to form part of a bigger case study focusing on the nature/extent of triple-helix dynamics in the fuel cell industry in South Africa.

As the study sought the opinions of experts within these CoCs as well as the opinions of industry and government entities, a qualitative approach was decided on as the most appropriate method to use, as qualitative research seeks a deeper understanding of the subjective experiences of individuals and how things operate in their natural environments (Starman, 2013: 30; Zainal, 2007: 4). Qualitative research is also associated with case studies viewed as a qualitative research/data collection method commonly used in educational research (Yazan, 2015: 134; Baxter and Jack, 2008: 544).

A case study, as defined by Simpson (2009: 29) and Starman (2012: 31), is an indepth exploration from multiple perspectives of the complexity and uniqueness of a particular project, policy, institution, programme or system in a 'real life' setting. Case studies usually focus on a single case or several small cases (sites); thus, the method for this study may be classified as a multiple-case study model as the focus was on three small cases (sites) represented by the three HySA CoCs (Rowley, 2002: 22; Starman, 2013: 35). The purpose of selecting these three CoCs was to identify the extent of each CoC's relationship with university, industry and government entities.

A criticism of the case study method is that it does not yet have well-defined and structured protocols, which leads to confusion about what case studies are and how they can be distinguished from other types of qualitative research methodologies (Yazan, 2015: 134). There is also the issue of generalisability, which relates to the fact that, in case studies, the generalisation of results stems mostly from theory rather than from populations (Zainal, 2007: 4; Hancock et al., 2009: 7). This relates to this study as it uses the triple-helix model for possible application to other similar contexts rather than to broader populations.

2.2.2 Sampling and sample

This study made use of purposive sampling to ensure that only relevant participants are selected. Purposive sampling can be seen as an informant selection tool, as informants are selected based on certain qualities they possess (Sarantakos, 2013: 475; Tongco, 2007: 147). This sampling technique was most suited as the information required would come from expert individuals situated in each of the HySA CoCs as well as fuel cell experts in industry and government entities.

It should be noted that, before the formal sampling process started, a preliminary informal interview/discussion was held with two experts in the industry, one being the director of HySA Infrastructure. They will not be named as they do not form part of the study sample. However, this informal discussion was vital for a better understanding of the fuel cell context in South Africa. The discussion led to the researcher attending a fuel cell launch at a clinic where key players from industry, government and universities as well as international entities were present. It was at this fuel cell launch where the researcher met the key informant (a fuel cell industry expert) who played an instrumental role in guiding the study. However, the document research formed the basis on which the participants from each CoC was selected and approached for participation. It was also through document research that the industry and government entities that have partnerships with each of the CoCs were selected for participation.

The formal sampling process started after the document research had been done, which led to the identification of the HySA initiative as a possible example of active triple-helix dynamics within the South African fuel cell context. The three CoCs hosted by NWU, UCT and UWC were then purposively selected as sites to study to form part of a bigger case study. Subsequent to identifying the CoCs, expert individuals situated at each of these CoCs were approached and invited to participate in the study.

As mentioned, document research showed that these CoCs not only had partnerships with government entities such as the Department of Science and Technology (DST), but also with industry players in the fuel cell field and science councils. Thus, purposive sampling was also used (using the information gained from the document research) to identify the key industry and government players, including science councils, with which these CoCs had partnerships. This was done to ensure that information collected on these partnerships could reflect the views of all parties involved in the partnerships (government, universities and industry).

2.2.3 Data collection

When collecting case study data, construct, internal and external validity during the research needs to be ensured. Construct validity is achieved through the triangulation of multiple sources of evidence to corroborate other findings (Rowley, 2002: 23; Yazan, 2015: 150). As this study focused on three small site studies operating in the same environment under the larger HySA initiative, evidence from each of these cases should typically be able to corroborate issues highlighted by each of them. Internal validity refers to the identification of patterns in the data, and external validity refers to analytic generalisations (Yazan, 2015: 150). These patterns and generalisation are discussed in the last two chapters.

The semi-structured interview was the tool used for collecting data for this study, as this technique permits the researcher to ask only the most relevant questions, while also allowing some degree of freedom to probe deeper if necessary (Sarantakos, 2013: 476). This allows for the possibility of identifying underlying factors vital for the study that were not thought of initially. Separate questionnaires were developed for the three types of entities participating in the study (universities, industry and government department), as participants needed to be asked about their specific contexts. Specific questionnaires for each entity facilitated the identification of themes, the analysis and the write-up process. It should also be noted that, over and above the notes taken by the researcher, all interviews were recorded to ensure accuracy during the transcribing phase. Participants were informed that, should any additional information be required, or clarity needed after the formal interviews, a questionnaire would be sent to them. This was the case in one of the interviews, where the participant cancelled the interview halfway through and sent through the answers to the remaining questions by email. It needs to be noted that this is a limitation in the data collection process, as it impacts on the researcher's ability to probe and get more indepth answers.

2.2.4 Data processing and analysis

Qualitative data analysis is based on examining, categorising and tabulating evidence to assess whether the evidence supports or contradicts the initial propositions of the study (Rowley, 2002: 23; Yazan, 2015: 134). It has been emphasised that there is no "one" way to analyse case studies (Rowley, 2002: 24). The data collected from the interviews followed the data analysing method proposed by Lacy and Luff (2009: 6). After the completion of the interviews the recordings and notes thereof were transcribed, sensitive data were anonymised where needed and the information was organised through colour-coding of themes identified. Thereafter, the next provisional categories were developed from the information and possible relationships between categories were explored, followed by a refinement of the themes and categories. To ensure findings could be corroborated or contradicted, the findings were compared with the pre-existing knowledge gathered though the literature review and document research. This was followed by "theory-testing" (triple-helix theory) against the data to establish whether triple helix dynamics do have the potential for developing a local, globally competitive fuel cell industry in South Africa.

2.3 Ethical considerations and limitations

Prior to the study field work, all possible participants were invited to participate by way of a formal email invitation explaining the purpose of the study. This was followed by the provision of participation information sheets as well as a letter of informed consent for signature. This letter addressed the research to be undertaken and the type of protocols to be used. Participants were assured of confidentiality and anonymity, where applicable. For this study, it was requested upfront that the companies/organisations be named. However, individual participants were guaranteed anonymity as the study sought to gain a broad understanding of the triple-helix dynamics in the fuel cell industry context, therefore rendering the disclosure of the specifics of individual participants unnecessary. A limitation to this study was securing a time slot to interview certain key people. In one case, the participant was overseas most of the time, which resulted in a Skype interview, followed by a section answered by email as mentioned above. Another limitation was getting access to key documents from companies, as most of these documents are not for public use.

2.4 Summary

Overall, this chapter outlined the methodology and methods used in the study. In this regard, the triple-helix model guided the methodology, focusing on university, industry and government collaborations in the fuel cell industry, with site studies done on the three CoCs, namely HySA Infrastructure, HySA Catalysis and HySA Systems. These CoCs were developed as a flagship programme by the DST, and were selected to gain a deeper insight into its level of engagement with universities, industry and government in the fuel cell context.

CHAPTER 3: THEORETICAL FRAMEWORK - TRIPLE-HELIX MODEL

The aim of this chapter is to provide a theoretical base for this study, which seeks to argue that developing a local fuel cell industry in South Africa can be facilitated only through active collaborative partnerships between university, industry and government institutions, as supported by the triple-helix theory. Some of the main ideas presented by this theory include the increasingly prominent role of the university in innovation, particularly through partnering with industry and government in a knowledge-based society; the movement toward collaborative relationships among the three major institutional spheres where innovation policy is generally the result of interactions rather than a prescription from government; and institutional spheres taking on the role of the others (e.g. industry adopting a training role) by performing activities in addition to their traditional functions (Anon, 2011: 1; Etzkowitz, 2008: 9; Etzkowitz and Leydesdorff, 2000: 111; Thune, 2010: 465; Ranga and Etzkowitz, 2013: 8; Leydesdorff, 2003: 1; Berawi, 2016: 1).

The chapter firstly provides a brief overview of the triple-helix theory, followed by a discussion on key concepts linked to the theory, including evolutionary economics, the knowledge-based economy, Mode 1 and Mode 2 knowledge production and technological catch-up. This is then followed by a discussion on the triple-helix model as a theoretical framework, starting with the neo-institutional perspective that emphasises the different triple-helix configurations in national and regional contexts, and then the neo-evolutionary approach, which emphasises how universities, industry and government co-evolve as subsets of social systems. Key concepts that fall under the neo-evolutionary perspective, including components, component relationships as well as their functions, will be discussed. The chapter concludes with a discussion on the applicability of the triple-helix model as a tool for developing a local, globally competitive, South African fuel cell industry.

3.1 Overview

The triple-helix model is widely recognised across developed and developing country contexts and used as a tool for understanding interactions between actors in the innovation system to inform innovation policies (Ivanova and Leydesdorff, 2014: 3; Etzkowitz and Leydesdorff, 2000: 109; Irawati, 2011: 161). Innovation systems are defined as sets of institutions that jointly and individually contribute to the generation, diffusion and use of knowledge for the development, circulation and application of new technologies (Lundvall et al., 2005: 293; Lundvall, 2005: 13).

The main assumptions of this approach are that links between industry (also referred to as “firms” in this study), research and development (R&D) institutes and other related components of the national innovation system contribute to generating, disseminating and using knowledge for innovation and that innovation policies are vital for establishing these linkages (Lundvall et al., 2005: 294). This is typically done through “absorptive capacity”, referring to a firm’s ability to recognise the value of new information, assimilate it and apply it for commercial purposes through transfer capacity, which in this context refers to a firm’s ability to transfer its knowledge across borders by establishing interconnections between entities such as university research centres and industry R&D laboratories (Lundvall et al., 2005: 294; Cohen and Levinthal, 1990: 1; Martin and Salomon, 2003: 357).

The triple-helix model was developed by Etzkowitz during the 1990s through the analysis of relationships between government and universities in different societies as well as the various roles these institutions played in innovation (Etzkowitz, 2008: 1; Ranga and Etzkowitz, 2013: 3). The model emphasises the importance of collaborations between universities, industry and government (institutional spheres) in creating an enabling environment for innovation through knowledge transfer in order to enhance economic development in a knowledge-based economy (Etzkowitz and Leydesdorff, 2000: 113; Ranga and Etzkowitz, 2013: 8; Leydesdorff, 2003: 1; Berawi, 2016: 1).

A triple-helix system is essentially initiated when the separate university, industry and government institutional spheres start interacting across robust boundaries. As these institutional spheres go through internal transformations, they gradually start to overlap with one another, blurring the previously robust boundaries and allowing easier and more regular interactions between the spheres. These interactions lead to the development of “spaces” that facilitate knowledge flow (knowledge transfer) and enable innovation. These spaces are categorised into the knowledge space, innovation space and consensus space, and will be discussed in more detail below (Saad and Zawdie, 2011: 1; Etzkowitz, 2002: 7; Irawati, 2011: 162; Harloe and Perry, 2004: 215).

The concept “taking the role of the other” is also key to the triple-helix model. It refers to when an institutional sphere adopts or internalises an additional function traditionally not linked to its key role. A typical example is the entrepreneurial university, where the university adopts an additional economic stance over and above its traditional function to train and conduct research (Anon, 2011: 1; Etzkowitz, 2008: 9; Etzkowitz and Leydesdorff, 2000: 1). Taking the role of the other is also a form of knowledge sharing between institutional spheres, as taking the role of the other may enhance not only each sphere, but also the performance of an existing industry (Etzkowitz, 2008: 8; Saad and Zawdie, 2011: 1; Subotzky, 2000: 70). However, this role may also cause universities to lose sight of critical thinking and become too business-oriented (Razak and White, 2015: 8). Some academics raise concerns about overemphasising university-industry collaborations, cautioning that it may lead to the contradiction of the values of academic freedom, long-term research and academic integrity through the increasing pressures for short-term research (Razak and White, 2015: 14).

The South African fuel cell industry, still at an early stage of development, is growing at a notable rate. However, as fuel cell technology is globally increasing in popularity, the country needs to ensure it remains at the forefront of this technology. This notion of remaining up to date with high-tech developments such as fuel cells links to the concept of technological “catch-up”, which refers to a developing country’s ability to learn and assimilate technology from countries at the frontier. This typically involves mastering new technologies, building a technologically sophisticated work force, and implementing new ways of organising and managing work as well as creative destruction, which refers to the process of challenging existing economic structures through innovative endeavours by combining knowledge in innovative ways to facilitate economic growth (Nelson, 2007: 16; Andersson et al., 2012: 3). South Africa is seeking to increase the economic benefits from its natural platinum resources, and this may be facilitated by assimilating fuel cell technology from areas such as Europe (a fuel cell technology leader). However, it may require strong triple-helix dynamics to facilitate knowledge transfer between the key players, especially from Europe to South Africa.

This thesis therefore argues in favour of triple-helix relationships, facilitated by strong collaborative partnerships between university, industry and government, for the possible successful development of a fuel cell industry in South Africa. The rest of the chapter will provide a more indepth discussion of the main foundations of the triple-helix model and its applicability to the study.

3.2 Evolutionary economics

The triple-helix model highlights the importance of knowledge transference between spheres such as university, industry and government, and inherently suggests that knowledge continuously evolves in an everchanging economic context. Therefore, an understanding of evolutionary economics is needed for the context of this thesis. Evolutionary economics is a scientific approach to economic analysis, which started in the 18th century with the conception of evolution which is a process at work in the economic realm (Potts, 2003: 1). The concept of evolution was generalised into the natural realm during the 19th and 20th century by Charles Darwin, and since then his followers have spread to contemporary domains such as evolutionary psychology, evolutionary politics and evolutionary economics (Potts, 2003: 1).

Economic evolution is concerned with the way knowledge grows as some ideas are tested and found reliable, while others are tested and rejected. Those rejected are redeveloped, mostly on variations of the same rejected ideas, and this is how knowledge grows (Potts, 2003: 3). Adam Smith generalised this and argued that specialisation was the key facilitator to growing knowledge (Potts, 2003: 3; Nelson, 2008: 10). At the heart of economics is the idea that wealth results from the coordination of specialised knowledge and that this process works best through a decentralised process of exchange (Potts, 2003: 5).

All economic systems are made up of knowledge. In an evolutionary economic process it is knowledge that evolves, capital is knowledge in an operational form and labour is knowledge in an active form (Potts, 2003: 6). As mentioned above, knowledge is subject to the evolutionary mechanisms (selection, variation and replication) that operate in institutions to produce the growth of the knowledge process known as economic evolution, which is what underpins a nation's wealth (Potts, 2003: 6; Lundvall et al., 2009: 296). The evolutionary theory acknowledges the economy as always being in a process of change, with economic activity proceeding in a context that is unfamiliar to the actors (Nelson, 2008: 10; Lundvall et al., 2009: 296). These actors, according to Nelson (2008: 10), have the ability to innovate around possible opportunities or adapt their activities in changing contexts. Therefore, economic progress needs to be understood as a learning process (Nelson, 2008: 10).

Schumpeter is seen as a key shaper of modern evolutionary theory, especially in the work of Sidney Winter and Richard Nelson (Nelson, 2008: 11). They highlight that Schumpeter's theory of economic development fails to recognise the institutional complexities of modern market economies (Nelson, 2008: 11). The innovation systems theory, however, enriches this theory in two overlapping ways. Firstly it recognises the complexity of several "market relationships, their embedding in broader social and institutional structures, and the elements of cooperation and trust that often are essential if markets are to work well" (Nelson, 2008: 12), and secondly it highlights the role of non-market institutions, such as university and public research systems, scientific and technical societies and government programmes, in the innovation process across sectors (Nelson, 2008: 12). While government policies and programmes are an essential part of the picture, these institutions are important because well-allocated basic research spending results in high expected social returns, with publicly funded research conducted at public institutions seemingly the best way of getting certain kinds of research done and results generally openly available (Nelson, 2008: 15).

The abovementioned innovation systems theory is an analysis of how knowledge evolves through processes of learning and innovation. Knowledge is the most valuable resource in an economy and learning the most important process (Nelson, 2008: 14; Lundvall, 2005: 11). Successful development can only occur through the co-evolution of technologies employed, firm and industry structure, and broader economic institutions, as also argued by the triple-helix model (Nelson, 2008: 15). Evolutionary economics further links to the ideal of triple-helix dynamics through its open frontiers, allowing for the interorganisational dialogue required for growth (Nelson and Winter, 2002: 42).

3.3 Knowledge-based economy

The knowledge-based economy is underpinned by the notion that knowledge is readily available as the main tool for economic development, which is also core to the ideal of triple-helix dynamics, focusing on the transference of knowledge for economic growth. Therefore, it can be said that triple-helix dynamics are in a way dependent on and interlinked with the knowledge-based economy.

The Organisation for Economic Co-operation and Development (OECD) defines the concept of knowledge-based economy as an expression used to describe trends in advanced economies towards a dependence on knowledge, information and high skill levels (OECD, 2005: 1). A knowledge-based economy relies more on intellectual capabilities than on physical inputs or natural resources, combined with efforts to integrate improvements at every stage of the production process, from the R&D laboratory to the factory floor to the interface with customers (Powell and Snellman, 2004: 200).

It was during the late 19th century that economists began to realise the importance of knowledge, with Alfred Marshall suggesting that knowledge is the most powerful engine of production (Cader, 2008: 118). The concept of the knowledge-based economy was first introduced by Foray and Lundvall at an OECD workshop in 1994, which resulted in a fuller recognition of the role of knowledge and technology in economic growth (OECD, 1996: 11). At this workshop Abramowitz and David emphasised the importance of making codified (generic) knowledge central to the analysis of a knowledge-based economy (Leydesdorff, 2010: 2; Powell and Snellman, 2004: 200). Abramowitz and David (1996) emphasised that, while "tacit knowledge continues to play a critical role in individual/organisational competencies and the localisation of scientific and technological advances, codification has been the favoured form taken by the expansion of the knowledge base" (Leydesdorff, 2010: 2).

However, in 1998 Antonelli suggested that the generation of new knowledge for economic growth, in the form of technological change, is the result of an interplay between generic knowledge and tacit knowledge, with generic knowledge referring to codified technological knowledge with direct scientific content, and tacit knowledge to learning processes based on the specific experience of the innovator (Cader, 2008: 118). Tacit knowledge is acquired through imitation, repetition and thus learning which takes long because life it limited, and learning takes time (Hausmann, 2016: 13).

The importance of interplay between tacit and codified knowledge is further emphasised by Hausmann (2016) indicating that economic development and technical progress is based on three aspects namely tools, codified knowledge and tacit knowledge which he refers to as the know-how. Tools can be shipped, and codified knowledge can be emailed, but tacit knowledge only exists as a wiring of the brain and is hard to move around which can easily become a binding constraint on the development process (Hausmann, 2016: 13). As tacit knowledge is difficult to pass on and takes longer than objective knowledge Hausmann (2016) also indicates that such knowledge can only grow at a society level through increasing specialisation by individuals.

In the 20th century Schumpeter considered this new combination of tacit and codified knowledge as an essential element for innovation and entrepreneurship, and saw technological change as the engine of economic growth (Cader, 2008: 118). It was indicated that these knowledge types work together, as scientific knowledge generation (general knowledge) leads to innovation (tacit knowledge) (Cader, 2008: 118; Powell and Snellman, 2004: 200). Generic, or codified, knowledge may be regarded as the material to be transformed and tacit knowledge the tool for transforming it (OECD, 1996: 13). Knowledge can be categorised further into four types: the first two is to “know-what” and “know-why”, which are typically obtained through books and lectures and also relate more to codified knowledge; the last two include “know-how” and “know-who”, typically obtained through experience and more associated with tacit knowledge (OECD, 1996: 12).

Interestingly, the development of information technology is believed to be in response to the need for handling the know-what and know-why portions of knowledge more effectively, while its existence gives a strong incentive to the process of codifying certain types of knowledge (OECD, 1996: 13). As information technologies are moving the border between tacit and codified knowledge, it requires a range of skills, typically classified as both tacit and codified knowledge. Therefore, now more than ever, skills in the form of tacit knowledge to handle codified knowledge is crucial in labour markets (OECD, 1996: 13). Especially in the emerging information society the labour force is increasingly handling information (codified knowledge) as opposed to the more traditional tangible factors of production (OECD, 1996: 13). Therefore, the knowledge-based economy is characterised by the need for continuous learning of both codified information and the tacit competencies to use this information (OECD, 1996: 13).

Linking to skills required in a knowledge-based society, a country's science system takes on increased importance, and public research laboratories and institutions of higher education are at the core. Government, science ministries, research councils, certain enterprises and other private bodies are all considered under this broad umbrella (OECD, 1996: 24). A science system contributes to new-knowledge production (research), knowledge transmission such as developing human capital (education and training) as well as disseminating knowledge by transferring it to economic and social actors, specifically to enterprises, whose role is to exploit such knowledge (OECD, 1996: 24).

In the science system universities are the main producers of knowledge, and they are acknowledged as such in a knowledge-based economy, while industry is the main actor for production, and government the source of contractual relations that ensure stable interactions and exchange between the players (Etzkowitz, 2008: 1; Harloe and Perry, 2004: 214). The significance of universities in the knowledge-based economy is further highlighted by the fact that, through producing knowledge, they also facilitate and drive product development (dependent on knowledge), while government and industry play supporting roles in academic development, typically in the form of resources, to enhance the performance of research (Etzkowitz, 2008: 9; 147). In addition, universities play an important role in the technical advancement of a country, as they are the principal trainers of industrial scientists and engineers as well as a source of research findings and techniques relevant to technical advances in industry (Nelson, 1993: 12).

Universities have moved away from concentrating solely on the dissemination of knowledge towards ensuring that knowledge produced by them is useful enough to be shared and translated into regional and national development (Saad and Zawdie, 2011: 1; Irawati, 2011: 162). The recognition of science's capacity for economically productive innovation, which involves a movement towards support for research that is closely linked to societal priorities, is increasing (Harloe and Perry, 2004: 215). Interdisciplinary research in the context of application and partnerships with industry and government has the potential to lead to new areas of research (Harloe and Perry, 2004: 214). Knowledge in the context of application therefore emphasises a strong relationship between different institutions and actors in the knowledge production arena, which requires universities to `reach out' and cooperate with industry and government, thereby highlighting the importance of triple-helix dynamics (Harloe and Perry, 2004: 214).

This cooperation between universities, industry and government (or triple-helix dynamics) forms the basis of the new combination of knowledge – an essential element for innovation. The knowledge-based economy, characterised by innovation, is interlinked with the triple-helix system and emanates from recognising the vital role of knowledge and technology in economic development (OECD, 1996: 9; Beesley and Cooper, 2008: 49; Nelson, 2007: 7; Harloe and Perry, 2004: 214). In a knowledge-based economy, knowledge is the most crucial resource driving development, while institutions are also emphasised as primary actors (Lundvall, 2005: 27). The knowledge-based economy is also known as a "network of networks", where technological linkages and knowledge flows between economic actors facilitate innovation that is driven by the rate of change and learning (Clark, 2011: 100; Jerome 2011: 20; Lundvall, 1999: 20).

For successful innovation, the role of triple-helix interactions in an increasingly knowledge-based economy such as South Africa, with enterprises and national economies dependent on the collection and utilisation of relevant knowledge, cannot be overemphasised (Etzkowitz, 2008: 1; OECD, 1996: 14). Innovation is not produced by research alone; it is through the support of mechanisms such as incubators, science parks, technology transfer offices (in universities, industry and government research laboratories) and business and financial support institutions, such as venture capital for new technology-based firms, that it is possible to harvest the economic potential of research and link science to the economy (Etzkowitz, 2008: 1; 90; 140; Benner and Sandström, 2000: 2; Jerome, 2011: 14; Thune, 2010: 465). These mechanisms are “hybrid organisations”, which originate from triple-helix collaborations.

Also important is distinguishing between exogenous and endogenous development strategies to create a knowledge-based economy. Exogenous development strategies focus on marketing local assets such as a trained workforce, good infrastructure as well as good living conditions, while endogenous development strategies recognise that local factors such as a strong knowledge base, skilled labour services and proximity to sources of knowledge and expertise are more important than cost reduction for high-technology firms (Ranga and Etzkowitz, 2013: 29). Innovative start-ups and smaller firms are more dependent on resources in their local environments, and creating the infrastructure for knowledge-based firm formation and growth is therefore the essence of an endogenous high-tech development strategy (Etzkowitz and Ranga, 2012: 22). A university-centred, long-term endogenous entrepreneurial approach is increasingly adopted to create “steeples of excellence” around emerging research themes with commercial potential (Etzkowitz and Ranga, 2012: 24).

Another characteristic of the triple-helix system is the ability to adapt its focus as the importance of producing knowledge and technology increases. This puts knowledge-producing institutions such as universities at the forefront in the attempt to create economic activity or to build up an old economy based on intellectual capital in the form of formal R&D (in government, universities and industrial laboratories) and tacit knowledge emanating from existing industries (Etzkowitz, 2008: 9; Etzkowitz and Leydesdorff, 2000: 113).

To sum up, a knowledge-based economy is not characterised only by innovation, but also by knowledge dissemination as well as the use and application of information and knowledge. This is vital for a high-tech industry such as the fuel cell industry (Pianta, 1999: 50; OECD, 1996: 15). In such high-tech industries high-level skills are required, which can be facilitated only through extensive investment in education, research and innovation. With the shift towards more relevant skills for economic competitiveness in a knowledge-based economy, universities should focus on these skills (Lundvall, 1999: 19; Harloe and Perry, 2004: 214). Although it is clear that investment in the development and supply of skills is essential for the development of a high-tech industry such as the fuel cell industry, the success of such an undertaking is reliant on having strong partnerships between the triple-helix actors, and this will be the focus of this study.

3.4 Mode 1 and Mode 2 knowledge production paradigms

Closely related to the knowledge-based economy is the type of knowledge being created, categorised as Mode 1 or Mode 2. In terms of Mode 1 and Mode 2 arguments, there has been a move from the old paradigm of scientific discovery (Mode 1) towards a new paradigm of knowledge production (Mode 2), which is application-oriented (Nowotny, et al., 2005: 1; Harloe and Perry, 2004: 214; Nowotny et al., 2001: 179; Kraak, 2000: 1; Leydesdorff, 2005: 1; Ivanova and Leydesdorff, 2014: 2). The fundamental differences between Mode 1 and Mode 2 can be specified along several dimensions.

Mode 1 solves problems that are set in a context governed by the interests of the academic community; it is disciplinary; it is characterised by a relative homogeneity of skills; it is hierarchical in organisational terms; it is not as socially responsive and reflexive; and it employs limited non-expansive quality control mechanisms (Gibbons, 2000: 35; Clark, 2011: 99; Leydesdorff, 2005: 1; Gibbons et al., 1994: 1). Mode 1 designates reliable academic knowledge produced within autonomous disciplinary contexts. Research in this context has limited links to social application, and boundaries between universities and industries are therefore not blurred and academics are quite autonomous in terms of choosing their research topics and problems (Tuunainen, 2002: 37; Gibbons et al., 1994: 1). Mode 1 is also characterised by the control of disciplinary science, with its strong sense of internal hierarchy between the disciplines, and is driven by the autonomy of scientists (Nowotny, et al., 2005: 1; Harloe and Perry, 2004: 214; Nowotny et al., 2001: 179; Kraak, 2000: 1; Leydesdorff, 2005: 1; Ivanova and Leydesdorff, 2014: 2).

In Mode 2 knowledge is created in a context of application involving a broad range of perspectives, with societal needs having a direct impact on knowledge production from the early stages of investigative projects (Tuunainen, 2002: 37). It is transdisciplinary (driven by transinstitutional communication across institutional borders); it draws on several disciplinary contributions and is able to set up new frameworks beyond them; it is heterogeneous; there is a preference for flatter hierarchies and organisational structures that highlight reflexivity; it is socially accountable and reflexive (indicating reverse-communication between science and society); and it employs an expanded system of quality control (for example, impact of research on society) (Gibbons et al., 1994: 4; Gibbons, 2000: 35; Kraak, 2000: 1; 18; Nowotny et al., 2001: 185; 179; Clark, 2011: 99; Leydesdorff, 2005: 1; Swan, et al., 2010: 1313; Nowotny, et al., 2005: 1; Harloe and Perry, 2004: 214; Kraak, 2000: 1; Leydesdorff, 2005: 1; Ivanova and Leydesdorff, 2014: 2; Tuunainen, 2002: 38).

It is argued by Tuunainen (2002: 39) that, when internal transformation of one of the helices (institutional spheres) highlighted in the triple-helix model is considered, the triple-helix model becomes parallel to Mode 2 knowledge production. When the university sphere takes on additional roles (the role of the other) such as the commercialisation of knowledge and becomes an entrepreneurial university, it too is characterised by Mode 2 knowledge production in the sense that it seeks to apply knowledge to society for economic development. Therefore, the triple-helix and Mode 2 approach complement each other and highlight the importance of applying knowledge to a social context for the development of an economy. Leydesdorff (2011: 26) argues in favour of the triple-helix model by stating that, by using the triple-helix model, analysis can be more specific than claiming a generalised transition from Mode 1 to Mode 2 in the new production of a knowledge economy. Tuunainen (2002: 18) provides an example of Mode 2 science where, in biotechnology, researchers are no longer trying to reveal the basic principles of the world, but are rather seeking to produce commercial applications and understand concrete systems and processes related to such applications. This is also indicative of the necessity of having various settings and practitioners involved in Mode 2 knowledge production, spanning from researchers from different academic disciplines to industrial scientists and other social actors (Tuunainen, 2004: 18).

Concerns regarding the Mode 2 argument are that the approach claims that science and the university, along with society, have changed and have become transgressive, referring to modern categories such as science, politics, culture and the market having become subject to the same co-evolutionary trends and therefore invading each other’s domain (Tuunainen, 2004: 26). The view has been criticised for leaving no room for science as a distinct social and cultural sphere, as if the segregation of science from non-science has vanished completely (Tuunainen, 2004: 26). Although there has been a general shift from Mode 1 to Mode 2, there is no clear historical indication where these two started to separate as distinct modes of knowledge production, or where Mode 1 lost dominance and Mode 2 started; the change has been gradual and, currently, these two modes co-exist (Tuunainen, 2002: 38). Mode 2 is not a new phenomenon; half of the discoveries in the 17th century had their origins in attempts to solve the problems of navigation, mining, etc. Mode 2 is, therefore, rather the original form of science prior to its institutionalisation into the university (Mode 1) in the 19th century (Tuunainen, 2004: 26). The difference is that, in the 21st century, the number of applications of Mode 2 is exponentially larger, driven rapidly by information and communication technology (ICT) capabilities.

3.5 Technological “catch-up”

Also mentioned previously is the notion of technological “catch-up”, which is necessary for a high-tech industry, such as the fuel cell industry, to thrive in South Africa through the support of triple-helix dynamics. Technological catch-up refers to a country’s potential and ability to reduce the technological gap between it and industry leaders through borrowing, imitating and adapting best practice from more productive and advanced economies with a view to pursuing the same path of development (Fagerberg and Godinho, 2004: 2; Abramovitz, 1994: 87; Juma and Clark, 2002: 4; OECD, 1996: 15; Nelson, 2008: 15). As the gap between the country catching-up and the country at the frontier decreases, the ability to create new knowledge and innovate increases (Fagerberg and Srholec, 2005: 32). Importantly, technological catch-up does not involve only imitating advanced technology for the same product, it may also relate to the development of a new product, and not necessarily to compete globally (Juma and Clark, 2002: 17). Innovative technologies are not developed only in the context of business seeking new routines, but also in contexts such as university or government laboratories and professional societies (Nelson and Winter, 2002: 38).

Historically, successful technological catch-up has been associated with both adopting existing techniques in established industries and innovating around modern technology (Fagerberg and Godinho, 2004: 2; Fagerberg and Srholec, 2005: 2; OECD, 1996: 15; Nelson, 2008: 15; Veugelers and Mrak, 2009: 32). However, catching-up is about much more than merely gaining mastery over modern technologies and building up a technologically sophisticated workforce able to work with them; it requires new ways of organising and managing work (Nelson, 2008: 17).

Innovation in any high-tech industry is a hands-on strategy that requires extensive science and technology policy capacity on the part of the government, industry and universities to be able to decide on the level and type of intervention or innovations needed (Irawati, 2011: 163; Isabel and Vargas, 2011: 25; Nelson, 2008: 15). Firms in developing countries that seek to catch-up (master modern technologies) require institutional instruments that can improve links with the technology frontier, markets, sophisticated users, suppliers of needed skills, and the local innovation system or network (Fagerberg and Godinho, 2004: 13). There also needs to be extensive investment in a highly trained workforce in the science and technology field, as these are crucial for innovation initiatives in 21st century science and technology, especially in high-tech industries such as the fuel cell industry (Nelson, 2007: 20).

Catching-up depends on a country's level of knowledge and technological capabilities. Technological capabilities involve a wide range of knowledge and skills to acquire, assimilate, utilise, adapt, change and create technology (Fagerberg and Srholec, 2005: 31; Juma and Clark, 2002: 17). Crucial to catching-up technologically are therefore efficient educational systems. This means that universities are crucial for implementing active research programmes to ensure the country is up to date with technological advancements, as well as for supplying trained engineers and applied scientists to enable manufacturing firms to catch-up (Nelson, 2007: 15; 19). It has been proven in countries such as Japan, Finland, Sweden, Korea, Taiwan and South Korea that raising tertiary education standards leads to technological innovation. Therefore, for South Africa to benefit from science and technology, its tertiary education system should drive growth and technological capabilities (Allard, 2015: 1). Only countries that invest in the formation of skills and R&D infrastructure seem to be able to catch-up successfully (Fagerberg and Godinho, 2004: 13).

Industrial and innovation policy should promote learning processes (the evolutionary perspective) that involve interaction between knowledge producers, such as universities, and firms. Technological catch-up indicates an inherent focus on capabilities as the main instruments for innovation and development (Lundvall, 1999: 31; Lundvall, 2005: 27). A country's prior capabilities are also crucial in determining the future rate and direction of technological change. Just as previous capital is needed to produce new capital, so previous knowledge is needed to absorb new knowledge, skills must be available to acquire new skills, and a certain level of development is required to create an economy where continuous development is possible (Juma and Clark, 2002: 8). Any country looking to enter global technological competition needs to ensure basic technological competence. Lacking this will most likely result in the country's failure to sustain advances in technological development (Juma and Clark, 2002: 17).

The links between universities, industry and government to facilitate the catch-up process through knowledge transfer cannot be overemphasised, as a firm's ability to accumulate technological capabilities is influenced by relationships (networks) with other institutional actors, and its innovative capabilities are determined by the extent to which it participates in knowledge networks, as innovation is an interactive process (Juma and Clark, 2002: 8; OECD, 1996: 3). In other words, through triple-helix dynamics and the transfer of knowledge a firm is provided with a knowledge base that will ensure it is aware of the current state of its specific industry and will allow it to innovate while continuously being up to date with newest developments. Innovation also moves through social networks, resulting from informal and formal communication processes. Networking between firms and knowledge bodies is key to successful technological catch-up (Juma and Clark, 2002: 9). A key concept relating to this is "absorptive capacity", which refers to a firm's ability to acquire, develop and implement new knowledge at the internal level (Maghe and Cincera, 2014: 7).

The speed of technology catch-up is dependent on institutional quality as it acts as an enhancing factor for technology transfer and promotes innovation (Manca, 2009: 27). Technological accumulation takes place at firm level, as this is where the necessary training is provided to enable absorption of new technology and to remain competitive, and where there is a real understanding of training needs, making firms suited for the acquisition of imported technology (Juma and Clark, 2002: 8). However, firms cannot do this in isolation from other economic entities, as they are all operating as organisms in an economy in which they are interlinked through the exchange of information, knowledge, finance, materials, staff, equipment and ownership (Juma and Clark, 2002: 8).

A study by Fagerberg and Srholec (2005: 69), focusing on 135 countries, indicated that the vital aspects for successful catch-up are knowledge, openness to technology/knowledge from abroad, the development of financial systems, the quality of governance and the degree of democracy. Knowledge is highlighted as the most critically essential element in the global knowledge-based economy, including a skilled labour force as reflected in educational standards/investments, R&D resources and a well-developed ICT infrastructure (Fagerberg and Srholec, 2005: 69). It was suggested that the observed shift in the conditions for catching-up may be a reflection of the radical technological change, with ICT-based solutions replacing earlier mechanical and electromechanical ones (Fagerberg and Godinho, 2004: 12).

Countries that have succeeded in catching-up have given a high priority to the knowledge dimension of development. However, the global knowledge-based economy is not static and for a country to remain competitive it needs to invest in the generation of knowledge capabilities continuously, which needs to be supported by efficient financial systems and governance (Fagerberg and Srholec, 2005: 69). Therefore, a country needs to be able to improve its knowledge capabilities continuously through the mobilisation of human, financial and administrative resources (Fagerberg and Srholec, 2005: 69).

It would not be viable to try to manufacture the exact technologies used in advanced countries, as the rate at which technology is adopted differs between sectors and depends on national contexts as well as firm-level characteristics (OECD, 1996: 15). However, this study argues that South Africa has the potential to adopt fuel cell technology from global fuel cell industries. Through active support of triple-helix institutional spheres, South Africa could continuously innovate around the technology and develop a local fuel cell industry that is able to compete globally.

3.6 Information and communication technologies

The catch-up process is made much easier through the development of information and communication technologies (ICTs). As disseminating knowledge is key to innovation, the use of ICTs can substantially increase a firm's technology uptake and innovation performance (OECD, 2012: 7). ICTs reduce the cost of accessing or diffusing information considerably, by enabling scientists and innovators from the developing world to access global scientific or business knowledge more easily (OECD, 2012: 7). ICT channels enable transference of ideas and can reach remote areas; they can also be used to facilitate innovation processes as new ideas are disseminated more widely and put to new uses (OECD, 2012: 20).

Challenges to tapping the full potential from ICTs include the need to have a widely available and affordable telecommunication infrastructure and to provide low-income groups with access to ICTs, which also requires better quality education to ensure an increasing number of people can take full advantage of ICTs (OECD, 2012: 20). Technological progress in countries seeking to catch-up usually entails the adoption and adaptation of pre-existing technologies that are new, either to the country or to the company into which they are transferred. This is dependent on whether the companies have access to the latest technologies and are willing to adopt them. ICTs are the technological backbone for innovations, and the impact of ICT industries as well as ICT applications for innovations in economic sectors is significant (Veugelers and Mrak, 2009: 32).

ICTs affect productivity and growth through rapid technological progress in the production of ICT goods and services and overall capital deepening, thereby helping to raise labour productivity by investing in sectors and helping individuals to increase their overall innovative efficiency (Veugelers and Mrak, 2009: 32). The successful use of ICTs may provide South Africa with the potential to adopt fuel cell technology and implementing it locally to become a global competitor.

3.7 Triple-helix conceptual framework

The triple-helix concept has developed into a source of innovation, organisational design and social interactions, and therefore provides a useful conceptual framework for the exploration of the dynamics of innovation and the knowledge-based society (Ranga and Etzkowitz, 2013: 3; Etzkowitz and Cai, 2008: 3). The theory may be useful for guiding national, regional and international policymakers in the design of innovation and development strategies. It may also encourage universities and firms to increase and strengthen their collaboration with triple-helix actors (Ranga and Etzkowitz, 2013: 3; Etzkowitz and Cai, 2008: 3). The triple-helix model can be looked at from two complementary perspectives, namely the neo-institutional and neo-evolutionary perspective. The systematic nature of triple-helix interactions is an underlying dimension of both these perspectives, which are not mutually exclusive (Stanford University, n.d.: 1; Ranga and Etzkowitz, 2013: 4).

Since the 1990s the neo-institutional theoretical perspective captured the imagination of scholars in academic fields who added to educational research, policy analysis, sociology, economics and organisation theory. It is one of the main perspectives used to understand organisational behaviour (Meyer and Rowan, 2006: 1; Lounsbury and Zhao, 2013: 1). The core idea behind this perspective is that organisations are deeply embedded in social and political environments, and organisational practices and structures are therefore often either reflections of, or responses to, rules, beliefs and conventions built into the wider environment (Powell, 2007: 1; Nee, 1998: 1).

Neo-institutionalism can be applied to various fields of study. However, especially relevant in the context of this thesis is the applicability thereof to the study of economic change and development, organisational change and the sociological study of institutions, as studied by Powell, DiMaggio, Scott and Nee (Meyer and Rowan, 2006: 1). The neo-institutional theory is closely linked to the triple-helix theory because of its emphasis on the possibility for unity of previously fractured institutions such as universities, industry and government and being driven by advances in interdisciplinary research directed at understanding and explaining key social problems (Meyer and Rowan, 2006: 1; Nee, 1998: 1).

The neo-institutional perspective looks at various triple-helix configurations in national and regional contexts. These configurations are indicated through the statist model, the laissez-faire model and the balanced triple-helix model (Ranga and Etzkowitz, 2013: 4; Stanford University, n.d.: 1; Ivanova and Leydesdorff, 2014: 3; Ranga and Etzkowitz, 2011: 252; Leydesdorff, 2011: 27).

By considering these models, a clear distinction is made between the driving forces of each, with the aim of emphasising why the structure of the balanced triple-helix model is vital for the development of a local fuel cell industry in South Africa. Each model highlights a different arrangement of the three institutional spheres, each representing a different system of society's key players, as discussed below.

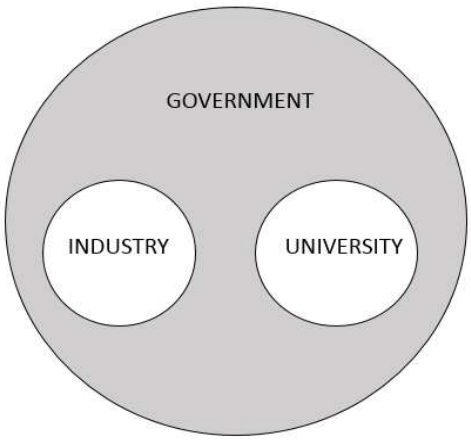

Figure 1: Statist model
Source: Ranga and Etzkowitz (2013)

In a statist society, government coordinates the relationships between the three institutional spheres, with industry and universities seen as weak and unable to function without guidance or control from government (Etzkowitz, 2008: 13; Cai, 2014: 1; Razak and Saad, 2011: 193). As government is the driving force in this context, it limits university and industry attempts at innovation. The society is characterised by specialised basic-research and applied-research institutes, including sectoral units from industries, and universities that are largely teaching institutions and are detached from industry (Etzkowitz, 2008: 14;

Razak and Saad, 2011: 193). The only advantage of this model is that industry and universities receive guidance and support from government. The model does not emphasise the ideals of a knowledge-sharing economy, which, as this study seeks to argue, is vital for the development of a fuel cell industry in South Africa.

Figure 2: Laissez-faire model
Source: Ranga and Etzkowitz (2013)

In a laissez-faire society, leadership is described as a non-leadership style, which avoids leading. South Africa's laissez-faire leadership is attributed to low levels of transformational behaviour from leaders, resulting in little job enrichment and poor relationships (Handley and Louw, 2016: 148). The country's National Development Plan (NDP) protects laissez-faire free-market policies such as less government "interference", more "flexible" labour laws, etc. According to Zwelinzima Vavi, the former Cosatu general secretary, this is a barrier to transformation (Vavi, 2016: 1), an indication that the country needs to move towards a balanced triple-helix interactive model.

In a laissez-fair society, industry, universities and government are separate from each other, interacting modestly across uncertain robust boundaries (Etzkowitz, 2008: 12; Razak and Saad, 2011: 193). In this context universities are seen as entities providing basic research and training on the one hand, and supplying industry with knowledge on the other (Etzkowitz, 2008: 15; Cai, 2014: 1). Industry operates in isolation in such a society, with interaction and collaboration between firms frowned upon. It is only through market relations that firms interact with one another (Etzkowitz, 2008: 15). In this instance the role of government is limited, with restricted interaction between universities, industry and government. If these relationships do exist, they happen across strongly defined boundaries and typically through intermediaries (Etzkowitz, 2008: 16). In this scenario industry can develop without unnecessary interventions by government, and collaboration between these spheres is very limited. And even though the model does indicate movement towards integration, this is hampered by uncertain boundaries.

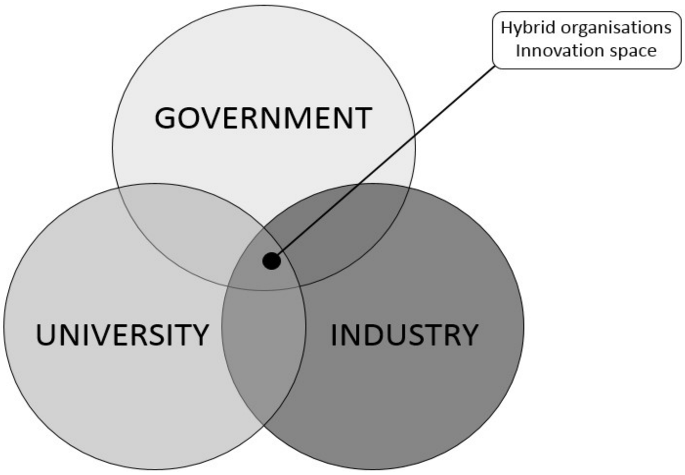

Figure 3: Balanced triple-helix model
Source: Ranga and Etzkowitz (2013) (modified)

The triple-helix (balanced) model is seen as the "ideal" societal system and has developed from the configurations illustrated in Figures 1 and 2 above (Etzkowitz, 2008: 12; Cai, 2014: 1). In a balanced society, the role played by universities and other knowledge institutions such as research institutes is continuously increasing, with these institutions often adopting the lead in joint initiatives (Ranga and Etzkowitz, 2013: 6). The type of institution that plays a prominent role in the joint initiative depends on the actual technology, as in some cases universities are the key role players and in other cases industry or government is key (Nelson, 1993: 15).

This model is considered as ideal for creating an innovation space at the centre where the three institutional spheres overlap, as indicated in Figure 3 (Etzkowitz and Leydesdorff, 2000: 111; Etzkowitz, 2003: 116; Ranga and Etzkowitz, 2013: 6). The model emphasises boundary permeability among the institutional spheres, meaning they can easily interact across blurred boundaries (Ranga and Etzkowitz, 2013: 3). Through this process a new space is created for interaction between institutional spheres, and new organisational formations are brought about by individuals and organisations taking the role of the other, also referred to as "innovation in innovation" (Etzkowitz and Leydesdorff, 2000: 111; Etzkowitz, 2003: 119). Taking the role of the other also enables institutional spheres to adopt additional roles. This strengthens the institution as well as existing industries, allowing for knowledge transfer and sharing. The innovation space created through cross-institutional interactions enhances innovation capabilities and enables the uncovering of new technology and the development of new firms and new types of relationships (Razak and Saad, 2011: 193). Based on this, South Africa as a developing country would benefit greatly by moving away from a laissez-faire society and adopting a balanced model that could steer the country into greater economic development.

In this model society has evolved from strong boundaries between institutional spheres, as indicated in the laissez-faire model (Figure 2), to a flexible, overlapping system of taking the role of the other, as shown in the balanced triple-helix model (Figure 3) (Etzkowitz, 2002: 2; Cai, 2014: 1). As internal transformation within institutional spheres occurs, they interact with other spheres across blurred boundaries, each increasingly "taking the role of the other" while still maintaining its own traditional role or traditional silo as Jerome (2011: 14) puts it. This results in each sphere more likely to become a source of innovation (Etzkowitz, 2008: 9; Razak and Saad, 2011: 192; Anon, 2011: 1; Etzkowitz, 2008: 9; Etzkowitz and Leydesdorff, 2000: 1; Subotzky, 2000: 70).

As the boundaries between institutional spheres become blurred, universities continue to perform their traditional role, which is to provide training and conduct research. However, through transferring knowledge and assisting with firm formation, universities take up additional entrepreneurial roles traditionally linked to industry, thereby shedding the traditional image and instead focusing on the production of useful knowledge and the exchange thereof across a wider network of key players in the socioeconomic system to become sources of new product development (Etzkowitz, 2008: 9; 147; Anon, 2011: 1; Thune, 2010: 465). As regards the development of a fuel cell industry, universities could take up the role of industry and, with the support of the fuel cell industry and government, their research findings could be commercialised for economic development.

As industry starts overlapping with universities, it may incorporate university-like training and research initiatives and become interested not only in the application of knowledge, but also in the production and sharing of knowledge, as well as the protection thereof (Thune, 2010: 465; Etzkowitz, 2008: 18; Gunasekara, 2006: 5; Irawati, 2011: 163; Harloe and Perry, 2004: 214). Within the sphere of developing a fuel cell industry in South Africa, if industry takes the role of the university, it may initiate inhouse training programmes for specialised skills within the fuel cell industry, which is typically the function of the university.

Government can take the role of industry in supporting relevant research and technology transfer to industry indirectly by supporting and setting up hybrid organisations (Thune, 2010: 465; Etzkowitz, 2008: 18; Gunasekara, 2006: 5; Irawati, 2011: 163; Harloe and Perry, 2004: 214). Government's role is to facilitate university-industry interactions through policy frameworks for defining research and development priorities in the light of prevailing socioeconomic circumstances and for allocating resources across these priorities (Saad and Zawdie, 2011: 1; Anon, 2011: 1; Etzkowitz, 2008: 9; Etzkowitz and

Leydesdorff, 2000: 1). The bulk of government R&D support, particularly in support of industrial R&D, goes into high-tech fields (Nelson, 1993: 516).

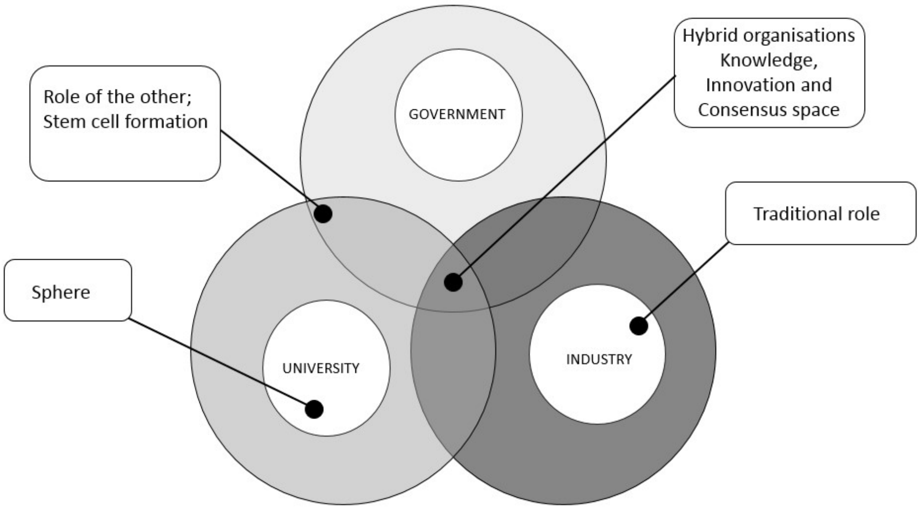

Figure 4: Triple-helix field interaction model
Source: Zhou (2014: 5) and Etzkowitz (2008: 19) (modified)

A concept that further details the triple-helix theory is the triple-helix field interaction theory. This concept is no different from the triple-helix theory shown in Figure 3, but it further illustrates the helices with both an internal core and an external field, which helps explain the institutional sphere's independence and interdependence, linking to the concept of "taking the role of the other" (Etzkowitz, 2008: 18). It is vital for individual institutional spheres to maintain their relative independence to ensure they retain their distinct character (Etzkowitz, 2008: 18). Thus, the triple-helix field interaction theory emphasises the importance of limiting the transformation from a laissez-faire model to overlapping spheres and not "reducing a statist model (too sharply) to retain each sphere's independence while facilitating interaction" (Etzkowitz, 2008: 19). This means that if government is too strong, a statist model might be formed, and if the interactions among the helices are too weak, it may lead to a laissez-faire model. This clearly emphasises the triple-helix model as the ideal.

The neo-evolutionary perspective or school of thought was developed from Charles Darwin's theory of evolution, discarding some views of the previous social evolutionism. Leslie White, the main theorist of this approach, emphasised that the evolutionary stages are abstractions applicable to the growth of human culture; culture grows out of culture with new combinations which are continually formed (Diah et al., 2014: 156). This perspective looks at how university, industry and government co-evolve as subsets of social systems (Ranga and Etzkowitz, 2013: 4). These institutional spheres evolve and are reshaped through market and network interactions as well as through innovation activities (Ranga and Etzkowitz, 2013: 4; Stanford University, n.d.: 1; Leydesdorff, 2005: 1; Leydesdorff and Deakin, 2011: 2). Relating the neo-evolutionary perspective to the triple-helix model, it is clear that economic development is not a spontaneous action, but “the outcome of policies, academic leadership qualities and corporate strategies, which all need to be carefully reconstructed, pieced together and articulated” (Leydesdorff and Deakin, 2011: 10).

As indicated above, the triple-helix system is defined as consisting of a set of components, relationships between the components, and their functions, which will be discussed in more detail below. The components of the triple-helix system refer to the institutional spheres of university, industry and government, each encompassing a wide-ranging set of actors, including R&D and non-R&D innovators, single-sphere and multisphere institutions, and individuals and institutions (Ranga and Etzkowitz, 2013: 8; Leydesdorff, 2011: 27).

R&D activities, technology adoption, assimilation and combining knowledge in different and new ways are among the vast number of methods that may increase an organisation’s innovative capacity (Ranga and Etzkowitz, 2013: 9). Each triple-helix institutional sphere has R&D innovators that typically include academic research groups and interdisciplinary research centres. Non-R&D innovators are typically associated with industry institutional spheres in the form of company actors mostly involved with market activities (Ranga and Etzkowitz, 2013: 10).

Single-sphere institutions would be a typical example of the statist model (Figure 1), as they function within the boundaries of a single institutional sphere and are characterised by high specialisation, work centralisation, limited mobility of workers, rigid and internal institutional boundaries, as well as limited interaction with other institutional spheres (Ranga and Etzkowitz, 2013: 11). Multisphere institutions (such as the entrepreneurial university) on the other hand would be a typical example of the ideal balanced triple-helix model (Figure 3) as these “multispheres”, as suggested in the name, function at the intersection of the university, industry and government institutional spheres – typically including science parks and technology incubators (Ranga and Etzkowitz, 2013: 11).

3.8 Relationship between triple-helix components

There are various forms of possible interactions that can take place between the triple-helix “actors”, typically including collaboration and conflict moderation, collaborative leadership and substitution (Ranga and Etzkowitz, 2013: 16; Leydesdorff, 2011: 27). Factors associated with cross-sector, interdisciplinary relationship building, such as good leadership, high levels of trust, transparency, enthusiasm and equality, are vital for creating an enabling environment for risk management and conflict resolution (Jerome, 2011: 15).

Collaboration and conflict moderation, typical in triple-helix entities, emphasise the potential of these entities to turn conflicts of interest into collaboration around common objectives (Ranga and Etzkowitz, 2013: 16). As the nature of work and workplace organisations are everchanging in a knowledge-based economy, the ability of turning tensions into common objectives is vital (Ranga and Etzkowitz, 2013: 16; Harloe and Perry, 2004: 215). Collaborative leadership interaction is a strategic decision by all involved to cooperate in order to achieve a common objective, and here individual or institutional innovation organisers play an important role (Ranga and Etzkowitz, 2013: 16; Leydesdorff, 2011: 25).

Substitution is similar, but not the same as taking the role of the other. It occurs when institutional spheres fill gaps that emerge in other spheres that are weak, and can occur between and within spheres at various levels (Ranga and Etzkowitz, 2013: 13; Karlsson, 2008: 10). A typical example of substitution is when government agencies, in addition to regulating and controlling, take up investment and the provision of public venture capital, which are traditionally linked to the industry sphere (Ranga and Etzkowitz, 2013: 14). When universities engage in technology transfer and firm formation, they enact some of the traditional roles of industry in addition to their teaching and research activities. Industry can also take on the role of the university by training and R&D development, which is often at the same high level as that of universities (Ranga and Etzkowitz, 2013: 14).

Substitution between spheres can occur also at country level where there are no or weak regional governments and where there may not be a governmental actor available to take the lead in promoting innovation developments. In such cases other actors such as universities and firms may come forward and assist in setting a future achievable objective (Ranga and Etzkowitz, 2013: 14). Substitution within spheres typically happens when vocational training institutions take the lead role over universities and collaborate with local firms – usually low-tech small firms (Ranga and Etzkowitz, 2013: 14).

Networking is also a vital form of interaction among the triple-helix system components and is found in substitution interactions (Ranga and Etzkowitz, 2013: 154; Park et al., 2005: 4). Networks are more flexible than hierarchies, are more invested in public goods than in markets, and take place within formal and informal structures as well as at domestic, regional, national and international level (Ranga and Etzkowitz, 2013: 14; 154; Park et al., 2005: 4). Innovative network dynamics are vital for these contexts as they promote cross-sector and cross-cultural interactions that are essential for the successful functioning of complex innovation systems (Jerome, 2011: 15). Networking reflects the increasing non-linear nature and interactivity of innovation processes (Ranga and Etzkowitz, 2013: 15). Research networks at universities act like a joint venture, the stability of which appears to be of critical importance in a social, political and economic context (Ranga and Etzkowitz, 2013: 15; Park et al., 2005: 4; Harloe and Perry, 2004: 214).

3.9 Summary

This chapter provides a theoretical base for this study, which seeks to argue that developing a local fuel cell industry in South Africa may be facilitated through triple-helix dynamics, that can be used to study innovation in a knowledge-based society. The triple-helix model emphasises the shift from separate institutional spheres (university, industry and government), each with strong boundaries, to overlapping spaces with no boundaries, thereby creating an environment for innovation through collaborative partnerships. The fuel cell industry in South Africa is still in its developmental stage, entering an unfamiliar context where there is engagement in the technological catch-up process. With strong triple-helix collaborations between universities, industry and government that enable assimilation, diffusion and innovation, the country has the potential to develop a strong, globally competitive fuel cell industry. Technological advancements in high-tech fields such as the fuel cell industry are driven by R&D facilities that are run by scientists and engineers trained through universities and attached to business firms, universities or government agencies. Following the triple-helix model, higher-education institutions should support the development of skills for the fuel cell industry, undertake research and transform knowledge and technology; industry should develop worker skills, share relevant knowledge with universities and ensure involvement in research and development projects for fuel cell development within universities and other research institutes; and government should take up a supporting role in research initiatives in the science and technology innovation space through polices and act as a funder and mediator between the education and industrial sectors. Through such strong collaborations between the triple-helix institutional spheres an ideal innovation environment focusing on fuel cell development could possibly be created, thereby also developing the industry. Therefore, the study argues for the adoption of the balanced triple-helix model for the possible facilitation of a local, globally competitive, South African fuel cell industry.

SECTION B: THE GLOBAL AND LOCAL FUEL CELL INDUSTRY

CHAPTER 4: FUEL CELLS AND THE GLOBAL FUEL CELL INDUSTRY

This chapter comprises two main themes, namely fuel cells in general and fuel cells in the global context. The first section focusing on fuel cells in general provides a history of fuel cell technology, followed by a discussion on the types of fuel cells currently available, the various types of fuel cell applications, the advantages and disadvantages of fuel cells as well as competing power technologies. The second part of the chapter focuses on fuel cells in the global context, with specific focus on how triple-helix dynamics facilitated the development of the fuel cell industry in countries considered to be leaders in the fuel cell field.

4.1 Fuel cells

Fuel cells are devices that create electricity by combining hydrogen, which is the fuel, and oxygen from the air over a catalyst such as platinum. It efficiently converts chemical energy into electrical energy and useful heat (Fuel Cell Today, 2012: 1; Johnson Matthey, 2016: 1). Platinum can be used as a catalyst as it is a substance that increases the rate of a particular chemical reaction without itself undergoing any permanent chemical change (Pagni, 2016: 1). The fuel cell concept was coined over 175 years ago in 1839 by William Grove, a chemist, physicist and lawyer. Grove's experiments ultimately proved that electric current could be produced from an electrochemical reaction between hydrogen and oxygen over a platinum catalyst (Jansen, 2016: 47; Fuel Cell Today, 2017a: 1). In 1889 Charles Langer and Ludwig Mond were the first to use the term "fuel cell" in their research on fuel cells using coal gas as a fuel (Fuel Cell Today, 2017a: 1). In 1932 Francis Bacon improved Langer and Mond's equipment to develop the first alkaline fuel cell (AFC); however, it was only in 1959 that he demonstrated a practical 5 kW fuel cell system (Fuel Cell Today, 2017a: 1). It was also around that time that Harry Karl Ihrig fitted a modified 15 kW Bacon cell to an Allis-Chalmers agricultural tractor, which led to a partnership between Allis-Chalmers and the United States Air Force for the development of various fuel-cell-powered vehicles (Fuel Cell Today, 2017a: 1).

The initial support of the National Aeronautics and Space Administration (NASA) provided the catalyst needed to launch the commercial fuel cell industry in the United States (U.S.). During the 1950s and 1960s NASA started developing fuel cell generators for manned space missions, which resulted in the invention of the proton exchange membrane fuel cell (PEMFC) by Willard Thomas Grubb, later refined by Leonard Niedrach through the use of platinum as a catalyst on the membranes (Fuel Cell Today, 2017a: 1; IDC, 2013: 15). Thereafter, in cooperation with NASA the Grubb-Niedrach fuel cell was further developed and eventually used in the Gemini space programme of the mid-1960s (Fuel Cell Today, 2017a: 1). Continuous efforts were made to better the technology. This led to the development of a 1,5 kW AFC for use in the Apollo space missions by International Fuel Cells, able to provide power and clean water for an entire space mission (Fuel Cell Today, 2017a: 1). This mission was a collaboration between government and industry players, emphasising a continuum towards possible triple-helix dynamics (NASA, 2017: 1). Since then NASA has been addressing aerospace challenges, dramatically advancing fuel cell technologies for aerospace applications with the aid of industry and universities, which indicates a move towards triple-helix dynamics (NASA, 2017: 1). In 1992 altogether 21 university research centres were created as result of partnerships between minority institutions and NASA (NASA, 2007: 1). Therefore, since the early 1990s, the importance of collaboration between industry, government and universities, and not just industry and government, became apparent. As fuel cells gained attention, they were also being developed for military applications in the Soviet Union, where they were used for onboard power for a submarine and later for the Soviet manned space programme (Fuel Cell Today, 2017a: 1).

Since then, governments, agencies and companies have invested substantially in the further development and refinement of the technology, as the energy produced by these fuel cells yields numerous advantages (Jansen, 2016: 47). NASA has made major investments in building research capabilities at the University research centres and partners research projects that contribute to space exploration, the knowledge of the earth and space, and the development of materials required for successful spaceflight (NASA, 2007: 1). The success of the university centres requires institutional commitment to the development of university research infrastructure and there should be active interaction with NASA and its contractors, small business and other major research institutions, emphasising the importance of triple-helix dynamics (NASA, 2007: 1).

Currently there are several types of fuel cells under development, each with its own advantages, limitations and potential applications (HySA Infrastructure, 2017: 1). Most fuel cells are powered by hydrogen, which can be fed into the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol and hydrocarbon fuels (HySA Infrastructure, 2017: 1). Even though most fuel cells are powered by hydrogen, fuel cell canals can also convert methane gas from wastewater treatment plants into electricity (EDD, 2011: 1; Smith, 2016: 1). This is, however, contradicted by Rayment and Scott (2003: 14), as they believe that, although there has been some discussion about the use of methane and carbon dioxide, these two sources are simply hydrogen carriers (Rayment and Scott, 2003: 14).

Fuel cells vary from tiny devices that produce only a few watts of electricity to large power plants that produce megawatts and are classified according to the kind of electrolyte they employ and which determines the kind of electrochemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors (HySA Infrastructure, 2017: 1; Fuel Cell Today, 2012: 1). These characteristics determine which applications these cells are most adequate for (HySA Infrastructure, 2017: 1; Fuel Cell Today, 2012; 1). Fuel cells are all based on the same design, using two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them. A catalyst is then used to speed up the chemical reactions at the electrodes (Fuel Cell Today, 2012: 1).

4.2 Platinum-based fuel cells

As indicated in table 1, there are six main types of fuel cells, which include the AFC, the PEMFC, the direct-methanol fuel cell (DMFC), the molten-carbonate fuel cell (MCFC), the phosphoric-acid fuel cell (PAFC), and the solid oxide fuel cell (SOFC). However, not all these fuel cell systems use platinum, and therefore, as the study focus is the utilisation of South Africa's platinum resources, only those that use platinum will be discussed further. From the list of the six main types of fuel cells only PEMFC, AFC and DMFC use platinum catalyst components in their fuel cell system (Fuel Cell Today, 2012: 1; Jansen, 2016: 48).

PEMFCs, also referred to as polymer electrolyte membrane fuel cells, deliver high-power density and, compared with other fuel cells, are low in weight and volume. They use a solid polymer as an electrolyte and absorbent carbon electrodes containing a platinum catalyst, and to operate they need only hydrogen, oxygen from the air and water, and they do not require harsh fluids like other fuel cells. These cells are fuelled with pure hydrogen supplied from storage tanks or onboard reformers (HySA Infrastructure, 2017: 1). PEMFCs operate at relatively low temperatures of below 100°C, and the electrical output can be varied, which makes them ideal for usage in vehicles (Fuel Cell Today, 2012: 1). PAFCs use liquid phosphoric acid as an electrolyte and absorbent carbon electrodes containing a finely dispersed platinum catalyst, and they operate at around 180°C. The PAFC is considered the "first generation" of modern fuel cells, as it is one of the most mature cell types and the first to be used commercially, typically for stationary-power generation (HySA Infrastructure, 2017: 1; Fuel Cell Today, 2012: 1). The electrical efficiency of PAFCs is relatively low, but overall efficiency can be over 80% if the heat is used (Fuel Cell Today, 2012: 1).

DMFCs use a platinum-ruthenium catalyst on the anode and a platinum catalyst on the cathode. They are powered by pure methanol, which is mixed with steam and fed directly to the fuel cell anode instead of hydrogen, and they operate in the range from 60°C to 130°C and are convenient for portable-power applications (Fuel Cell Today, 2012: 1). These fuel cells do not have the fuel storage problems typically experienced by other fuel cells, as methanol has a higher energy density than hydrogen. Methanol is also easier to transport and supply to the public by means of the current South African infrastructure, as it is liquid (HySA Infrastructure, 2017: 1).

Table 1: Fuel cell technologies and applications
Source: IDC (2013)

	Operating temperature	Electrical efficiency	Typical electrical power	Application
PEMFC	80°C	40-60%	<250 kW	Vehicles, small stationary
DMFC	60-130°C	40%	<1 kW	Portable
MCFC	650°C	45-60%	>200 kW	Stationary
PADC	200°C	35-40%	>50 kW	Stationary
SOFC	1,000°C	50-65%	<200 kW	Stationary
AFC	60-90°C	45-60%	>20 kW	Submarines, spacecraft

4.3 Fuel cell applications

Fuel cells can be used in a variety of applications that can be divided into three main categories, namely portable power, stationary power and transportation power (EESI, 2015: 1; HySA Infrastructure, 2017: 1; Smith, 2016: 1). Portable-power systems or fuel cells are highly mobile electricity generation units used for directly powering electronic equipment, recharging batteries or providing power for numerous consumer electronic products (on-the-go power). They can also provide emergency power (off-grid power) for homes and offices (FCHEA, 2017: 1).

Fuel cells in the stationary-power category are often used as primary or backup power for large energy infrastructure and have three main uses, namely combined heat and power (CHP), uninterruptible power supplies (UPS), and primary-power units (EESI, 2015: 1). CHP systems use both heat and electricity generated by the fuel cell to maximise fuel efficiency and run at 80-95% efficiency, while UPS systems are sources of uninterrupted power and are primarily used to provide backup power (EESI, 2015: 1). These systems are able to replace diesel-powered emergency generators in critical facilities (EESI, 2015: 1). Primary-power units are large stationary units that can be used to generate and supply electricity to the grid or other facilities (EESI, 2015: 1).

Fuel cells can also be used in the transport sector to power scooters, forklift trucks, buses, trains, boats, aircraft and cars. These have been implemented in South Africa, as discussed below in this chapter. Fuel-cell-powered forklifts have been very popular among customers such as Coca-Cola, BMW and Walmart, while several automakers are engaged in fuel cell electric vehicle research and development (R&D) partnerships (EESI, 2015: 1; HySA Infrastructure, 2017: 1).

4.4 Advantages and challenges of fuel cell technology

The hydrogen used in fuel cell technologies has numerous advantages. These typically include that it is non-toxic; it is less flammable than gasoline; it disperses quickly into the atmosphere as it is 15 times lighter than air; if spilled it becomes rapidly sparse and difficult to ignite; if it catches fire, it burns itself out quickly; it can be stored safely as the tanks it is stored in undergoes demanding testing procedures to ensure they can endure extreme heat and external pressure forces as well as collision impact; it has a high efficiency rate; it is clean due to it being carbon-free when using molecular hydrogen and oxygen molecules (FCHEA, 2017: 1).

The advantages of the actual fuel cells are that they can use a range of renewable fuels; they do not require recharging; they can run continuously without interruption; there are no moving parts; and they are virtually silent, making them ideal for residential zones (HySA Infrastructure, 2017: 1). Fuel cells are also highly scalable, and therefore easily made larger or more powerful; they are well-suited to distributed generation, which relates to the generation of electricity from various small energy sources; they can be used near to where the electricity will actually be used; and they can be run in reverse for energy-storage-producing hydrogen from electricity and water (Martin, 2009: 5; Sigel, 2012: 1, U.S. DoE, 2014: 21; HySA Infrastructure, 2017: 1; Smith, 2016: 1). Environmental concerns are increasing globally and as fuel cells are carbon-free and classified as a green technology, they may be the answer to the global demand for cleaner power and technology, promoting the Green Economy initiative globally as well as in South Africa. However, it needs to be noted that, although this one is of the major advantages of fuel cell technology, it is not the main focus of this study. This thesis focuses more on the manufacturing side of the technology as mentioned before.

Additionally, the fuel cell value chain may provide employment opportunities, which can be divided into the “primary supply chain” category and the “field deployment services” category (Anglo American, 2013: 1). The primary supply chain consists of catalyst production, membrane electrode assembly (MEA) production, stack assembly, component production, subsystem assembly and system integration, while the field deployment consists of delivery, quality checking and so on, which is the stage at which lower-level skills are required (Anglo American, 2013: 1).

Although fuel cells come with a multitude of advantages, inherently there are also challenges that act as barriers to the development of the industry, which relate to the applications in which these technologies are used. Some of the broad challenges typically include insufficient market penetration, reliability, durability, size, weight, thermal and water management, as well as cost implications especially in the South African context (Jansen, 2016: 47). The U.S. Department of Energy (U.S. DoE) (2015: 185) states that platinum is the major contributor to the cost of fuel cells. Another element contributing to the high cost of fuel cells, especially in South Africa, is the small demand for the product. However, as market adoption increases the cost should automatically come down (Jones and Botha, 2014: 317). According to Rayment and Scott (2003: 13), the high initial cost of fuel cells can be attributed mainly to the high cost of manufacturing associated with each type of fuel cell, with an additional contributor being the lack of adequate infrastructure to deliver fuel cells to these technologies. This is mainly due to the unfamiliarity around fuel cells. To address this, a specific type of fuel cell needs to be chosen to ensure the correct development of an infrastructure that supports its specific needs (Rayment and Scott, 2003: 13).

Challenges around the commercialisation of the technology include, among others, the search for renewable hydrogen; the rollout of hydrogen infrastructure; meeting and exceeding customer expectations; cost versus price; market competition; inadequate policies; and a lack of awareness. Therefore, the initial focus in developing the industry should be policy change in the form of standardisation, safety codes and regulations for the production and distribution of fuels, as well as familiarising the power industry with this emerging technology (Rayment and Scott, 2003: 14; Patterson, 2013: 6). In addition, a key challenge for the development of a fuel cell industry, globally and locally, is the issue of competing power technologies as discussed below.

4.5 Competing power technologies

As with any innovative technology, fuel cells have power generation competitors, namely solar panel power, wind turbine power and battery power. Wind and solar power offer increased operational efficiency and the elimination of carbon emissions, but the disadvantage for both these alternatives lies primarily in their inability to generate energy constantly, which is not the case with fuel cell technology (Tracy, 2016: 2). To gain a better understanding of why fuel cells should be considered a more attractive technology for power generation, a discussion follows on the advantages and disadvantages or limitations of these technologies for different applications in relation to fuel cells.

Solar energy comes with its own advantages and limitations. On the positive side, solar energy converts the sun's energy into electricity and therefore does not release any harmful emissions such as carbon dioxide, methane or other emissions into the air (Solar Facts and Advice, 2017: 1). However, activities such as the manufacturing, transportation and installation of solar panels are accompanied by some of those emissions (Solar Facts and Advice, 2017: 1). Also, solar power is silent and therefore does not interfere with wildlife or residential areas; it does not require connection to the power grid and is reliable with no moving parts that require replacement; and it can save money in the long-term despite the high initial installation cost (Solar Facts and Advice, 2017: 1).

Despite these advantages, a major limitation is that solar energy does not work at night and, although it can still be collected during cloudy and rainy days, the efficiency of the solar system drops during days of limited sunshine (Understand Solar, 2017: 1). A fuel cell system does not have this limitation as it can run uninterrupted throughout the night. Solar panels also have limited movement potential, as they are mostly installed on roofs and although it is possible to take the solar system, together with the lease of contract with when you move, the de-installation and re-installation costs are high (Understand Solar: 2017: 1; Green Match: 2017: 1). Fuel cells offer more options regarding the size and type (portable or stationary) as mentioned before and are therefore a better alternative in this regard. Solar energy also needs to be used right away or can be stored in large batteries, which can be charged during the day for energy at night. However, this is a very expensive alternative (Green Match: 2017: 1). Fuel cells on the other hand generates power continuously and uninterruptedly, and evidently offer the better alternative as it is more reliable and efficient.

Wind turbines are noisy and are therefore situated far from residential areas, while fuel cells are basically silent and easily used at any site, making them a better alternative to wind power (Johnson, 2017: 1). A major issue with wind turbines is their negative effect on wildlife, especially those in the sky and underground (Johnson, 2017: 1). This is especially true for migratory birds that tend to fly into the blades, with studies showing that about 45 000 birds have perished over the past 20 years due to these turbines (Johnson, 2017: 1). Underground habitats are also disturbed due to deep digging, while fuel cells do not affect wildlife in any way (Johnson, 2017: 1). The environment is further impacted in terms of the sizable "carbon footprint" of turbines caused by their production, transport and installation, despite the whole idea behind the creation of clean power (Johnson, 2017: 1).

To be effective turbines require wind, which is an unpredictable resource and not as widely found as generally assumed. When wind energy is converted into usable electric energy, the wind turbine's internal machinery is able to extract only about 59% of the wind's power, highlighting that it is not very efficient (Johnson, 2017: 1). Wind turbine technology is therefore not as efficient as other alternatives on the market. The installation cost of wind turbines is also very high, escalated even further by maintenance costs, while fuel cells, although also on the pricy side, do not require as much maintenance (Johnson, 2017: 1).

Cook (2001: 14) foresaw in 2001 that fuel cells may one day replace gasoline and diesel engine generators for portable applications as well as conventional batteries for uses such as remote lighting, laptop computers and cellphones. Battery-powered sources have been the lead power supply technology for portable applications for a long time, but it seems as if the technology is proving to be insufficient in providing increasing device operating time, which means that increased charging is necessary (Kundu and Dutta, 2016: 122). This has led to serious concerns about the modernisation of portable electronic devices, specifically devices used in emergency and military operations where changing is not always possible (Kundu and Dutta, 2016: 122).

As technology advances and our dependence on portable electronics increases, so does the demand for powering these devices. In this regard fuel cells, and specifically hydrogen fuel cells, act as an attractive alternative for replacing batteries, as they potentially offer five to 10 times greater energy densities than rechargeable batteries (Rayment and Sherwin, 2003: 119). Advantages of portable power stacks that use fuel cells include that they can produce the same amount of energy as batteries, while being much smaller and lighter; they can instantly be charged by being replaced with a refilled cartridge; they have a longer cell life; they operate at a low temperature; and they are more efficient at energy conversion (Cook, 2001: 15; Kundu and Dutta, 2016: 124). In addition, rechargeable batteries lose capacity and are eventually discarded, contributing to landfill contamination with metals such as nickel and cadmium. Disposing of fuel cells is therefore less detrimental to the environment when compared to batteries (Potera, 2007: 1). Fuel cells do not discharge and degrade over time, the metal hydride should not wear out – although it could deteriorate through excessive practical use – and they do not short or overload, while batteries can malfunction and have a limited life span (Potera, 2007: 1).

A possible challenge for the further development of fuel cells for use in miniature portable devices may be that the technology is much more complex than batteries (Kundu and Dutta, 2016: 124). However, progress has been made in micro-electromechanical system technology and its application in manufacturing different fuel cell component parts, which indicates the possibility of miniaturising fuel cell devices to make them compatible with miniature portable electronic devices (Kundu and Dutta, 2016: 124). The main drivers for portable fuel cell applications remain off-grid operation, longer run-times compared to that of batteries, rapid recharging, significant weight reduction potential, convenience, reliability and lower operating costs (Fuel Cell Today, 2017b: 1; FCHEA, 2017: 1).

Both fuel cells and batteries can be used for stationary applications. However, the advantage of fuel cell technology when compared to batteries is that they are not sensitive to extreme heat or cold, making them most adequate for outdoor applications (Kubert, 2010: 3). Batteries are not adequate for outdoor stationary applications as they are sensitive to extreme heat and cold and, due to declining performance, need to be replaced every few years (Kubert, 2010: 3). Two primary applications for fuel cells in critical facilities include using them strictly for standby power in the event of grid failure or using them as a high-quality source of primary power for the facility that will also continue to provide uninterrupted power during an electrical outage (Kubert, 2010: 3).

Considering the advantages of fuel cells and batteries for use in transportation is also important. Although battery range is improving, it remains limited and it takes approximately half an hour to recharge an electric vehicle, provided a 480 volt fast-charger is available (currently very rare) and the vehicle is equipped to handle it, otherwise it can take hours (Gorrie, 2016: 1). If the travel distance falls within the vehicle range, it can simply be plug in at home and recharged overnight; however, for longer trips a non-battery vehicle is required, and the fuel cell vehicles would be provide for this requirement (Gorrie, 2016: 1). Fuel cell vehicles refuel within three minutes, each fill lasting 500 km or more and, unlike batteries, they do not lose capacity in cold weather (Gorrie, 2016: 1), as mentioned above. Fuel cell vehicles are very efficient – more than three times as efficient as today's average gasoline-powered vehicles (Samuelsen, 2016: 1).

Both fuel cell electric vehicles (FCEV) and battery electric vehicles have electric drivetrains, battery packs and regenerative braking. However, they differ fundamentally with regard to their respective source of electricity, time required to recharge or refuel, driving range, and the ability to scale up the size of the vehicle (Samuelsen, 2016: 1). Battery electric vehicles are best suited to light-duty vehicles such as delivery trucks and buses on routes of modest range, while it requires more battery mass to power larger, longer-distance vehicles with batteries. These vehicles would need a bigger motor, a stronger suspension and better brakes to maintain the same performance, all adding more weight, which means bigger batteries are required (Samuelsen, 2016: 1). Fuel cells, on the other hand, can be used to power virtually any size vehicle. It is therefore about which power source is best suited to the requirements and context, not necessarily which technology supersedes the other (Samuelsen, 2016: 1). It is evident that from the discussion above that fuel cells have a distinct advantage over current energy generation technologies, from high efficiency to scalability, and this is why top companies, governments and the military are adopting fuel cells for everyday use.

4.6 Fuel cells in the global context

A global fuel cell perspective is necessary to place South Africa's fuel cell industry in context, especially since it is a developing industry. This section will focus on the key global players in the fuel cell market, which include the U.S., Japan, Germany and South Korea (U.S. DoE, 2014: 41). Specific focus will be placed on the current state of the fuel cell industry in each of these countries, and consideration will be given to how education and R&D initiatives support the industry. It needs to be noted that this section is by no means an exhaustive list of all activities in the fuel cell industry in these countries. The aim is to uncover possible triple-helix dynamics taking place in the industry within these countries. To this end examples are discussed below on triple-helix dynamics in the fuel cell context of each of these countries. South

Africa's fuel cell industry is still at the developing stage, and it is hoped that, through this review, it will be possible to identify where the country's fuel cell industry is falling short and what examples these countries hold for us with a view to improving the South African industry. In addition to the information in Table 2 below, indicating which international firms have a presence in South Africa, Ballard Power, Clearedge, Toshiba, Panasonic, Plug Power Inc. and Hydrogenics Corporation have also established themselves in South Africa (IDC, 2013: 19).

Table 2: List of global fuel cell producers
Source: IDC (2013)

Firm	Country	Type	Presence in South Africa
Bloom Energy Servers	U.S.	Energy servers	No
Altergy	U.S.	Portable fuel cell generation systems	Yes
Panasonic Ene Farm	Japan	Residential fuel cells	Yes
Toshiba Dynano	Japan, U.S.	Portable fuel cells	Yes
Daimler Benz	Germany	Fuel cell electric vehicles	Yes
Toyota	Japan	Fuel cell electric vehicles	Yes
Nissan	Japan	Fuel cell electric vehicles	Yes
Fuel Cell Energy	U.S.	Stationary fuel cell power plants	No
Antig	Taiwan	Fuel cell stacks	No
CMR Fuel Cells	United Kingdom	Direct-methanol fuel cells	No
Nomadic Fuel Cells	U.S.	Direct-methanol fuel cells and proton exchange membrane fuel cells	No
Samsung	South Korea	Fuel cell batteries	Yes
Horizon Fuel Cell Technologies	Singapore	Proton exchange membrane fuel cells	No
myFC	Sweden	Portable fuel cells	No
Volvo	Sweden	Fuel cell electric vehicles	Yes

4.6.1 Fuel cell industry in the United States of America

In 2015 more than 60 000 fuel cells were shipped worldwide (U.S. DoE, 2015: 1). Technology is therefore becoming an integral part of the energy mix globally, leading to international opportunities for various U.S. companies (Curtin and Ganji, 2014: 1). Several states in the U.S. have realised the potential of fuel cell technology as a high-growth industry to facilitate job creation and increase economic benefits (U.S. DoE, 2014: 3). Therefore, the U.S. fuel cell industry has taken off and is now at the forefront of the industry worldwide (U.S. DoE, 2014: 1). The U.S. is home to leading fuel cell manufacturers in different market sectors, including large-scale power generation, backup power for telecommunications and data centres, primary power for material handling equipment and many key supply chain companies for components such as bi-polar plates, membranes and catalysts, and hydrogen fuel (U.S. DoE, 2014: 3).

In the U.S., fuel cell technology is not new to municipalities, as the technology was demonstrated in this field in as early as the 1990s. The early installation helped with the improvement of the technology and familiarised stakeholders with the logistics around the technology (Curtin and Ganji, 2014: 16). Some fuel cell applications include, among others, supplying power to public-funded sites such as schools, zoos and jails (Curtin and Ganji, 2014: 2). Currently, several of the largest industrial corporations in the U.S. such as Apple and Adobe are using fuel cells for various tasks. This first started small by testing fuel cells at a few sites with the support of the U.S. DoE before they invested further in the technology (Curtin and Ganji, 2014: 1).

An exciting development is that of Boeing and Airbus, both leading airplane manufacturers. They are researching and demonstrating fuel cells for use on planes, both for propulsion and for auxiliary power (Curtin and Ganji, 2014: 28). Fuel cells are also used for roadways in the form of delivery trucks, material-handling vehicles at warehouses, ports, airports and railroads (Curtin and Ganji, 2014: 26). The U.S. DoE funded two fuel cell truck refrigeration unit demonstration projects to power the trailers that carry refrigerated and frozen goods to grocery stores and restaurants (Curtin and Ganji, 2014: 26). Fuel cells can also be used to power locomotives or hydrogen-fuelled trains as well as to provide backup or remote power to switches, signals, railway crossings, monitoring and communications equipment, and to power security cameras at the rail yard (Curtin and Ganji, 2014: 29). The above are just a handful of examples of applications where fuel cells are helping to make a difference and save money for companies and municipalities across the U.S., while also reducing emissions and power outages for citizens.

In May 2012 the U.S. DoE launched a modelling tool for estimating the economic benefits of fuel cells in early-market applications (U.S. DoE, 2016: 1). This tool estimates the number of jobs created by deploying fuel cells for forklifts, backup power and prime power applications, and is referred to as Job and Output Benefits of Stationary Fuel Cells (JOBSFC) (Mintz et al., 2012: 3; U.S. DoE, 2016: 1). The model was upgraded in 2014 and can now estimate employment as well as revenue impact of infrastructure development to support early-market FCEV penetration (U.S. DoE, 2016: 1). Using an input-output methodology, the model can estimate changes in industry expenditure and calculate the ripple effects of those changes throughout the economy (U.S. DoE, 2016: 1). The output is presented in a spreadsheet, with estimates of the economic impact from the manufacture and use of select types of fuel cells (U.S. DoE, 2012: 1). The Job and Output Benefits of Hydrogen (JOBSH2) model uses the same model structure and methodology as the JOBSFC model and estimates changes in industry expenditures due to hydrogen fuelling infrastructure deployment, and calculates the effects of those changes in the economy (Mintz et al., 2013: 12).

Occupations for the fuel cell industry, specifically in the U.S., include mechanical, industrial, chemical engineers and electrical engineers; materials scientists; chemists and laboratory technicians; factory workers; machinists; power plant maintenance staff and operators; bus, truck and other fleet drivers; vehicle technicians; fuelling infrastructure installers; and hydrogen production technicians (U.S. DoE, 2016: 1). It is estimated that the U.S. fuel cell industry could create up to 180 000 new jobs by 2020, and 675 000 jobs by 2035, provided there is widespread market adoption of the technology (U.S. DoE, 2016: 2). The above occupations should also be applicable to the South African fuel cell industry, depending on the level of development of the industry.

The South African Department of Higher Education and Training (DHET) has developed a tool called the National Career Advice Portal (NCAP), which indicates the career path for South African occupations. When considering the occupations highlighted above, the tool indicates that South Africa currently has seven universities offering a degree in mechanical engineering; three universities offering a degree in industrial engineering; seven universities offering a degree in chemical engineering; nine universities offering a degree in electrical engineering; one university offering a degree as well as a diploma for materials scientists; and 13 universities offering a degree for chemists. Also, no formal education is required for factory workers as they will typically undergo workplace learning offered by an employer; machinist is classified as a trade and students will therefore need to complete a trade test; bus, truck and other fleet drivers will be required to get the necessary driving licence (NCAP, 2017: 1). The NCAP tool also indicated that there are no specific qualifications or courses in South Africa offered for power plant maintenance staff, power plant operators, laboratory technicians, vehicle technicians, fuelling infrastructure installers and hydrogen production technicians (NCAP, 2017: 1).

In the U.S. various projects that have been designed around introducing fuel cell technology not only into the schooling system, but also especially into the university system to educate the scientists, engineers, and potential end users of tomorrow (U.S. DoE, 2017: 1). To this end fuel cell education models were designed and funded by the Fuel Cell Technologies Office (FCTO) and are implemented at various universities in the U.S. (U.S. DoE, 2017: 1). Projects offered comprise general education courses, specialised science and engineering courses, minor and concentration programmes, curriculum modules, internships, laboratory classes and kits, as well as textbook chapters (U.S. DoE, 2017: 1).

As far as triple-helix collaborations are concerned, the U.S. fuel cell industry serves as a prime example of how these collaborations can facilitate the development of a successful high-tech industry. U.S. university and college research centres partner with industry to educate and train future generations of engineers and scientists, and provide highly skilled technical researchers and workers (U.S. DoE, 2014: 3). Specific courses and degrees in fuel cell technology are offered by many colleges and universities, thereby generating the required skills for the industry. It is through these contributions to skills development that the various entities attract federal funding to support fuel cell and hydrogen research, development, demonstration and R&D activities (U.S. DoE, 2014: 3). This is the essence of what the triple-helix model; the formula needed for such an industry to succeed is university institutions developing the required skills (specialists and researchers), as informed by industry, and receiving funding from government. This is further supported by the numerous U.S. policies for the development and deployment of fuel cells, while additional state agencies make funding, grants and low-interest loans available to fuel cell companies and researchers (U.S. DoE, 2014: 15; Curtin and Ganji, 2014: 19).

The U.S. DoE, through its Energy Efficiency and Renewable Energy (EERE) FCTO, is a main player in supporting the fuel cell industry as it funds research, development and deployment projects and programmes such as the "Small Business Innovation Research and Small Business Technology Transfer" (U.S. DoE, 2014: 15). All these initiatives around the fuel cell industry in the U.S., and the development of expertise and activity, are helping to advance the fuel cell industry around the world, while also generating jobs and economic investment for the country. The U.S. clearly has the support from industry, universities and government, indicating the presence of triple-helix dynamics that sustain its fuel cell industry and may hold key lessons for South Africa.

4.6.1.1 Factors that facilitated the development of a successful fuel cell industry in the U.S.

California, Connecticut, New York and South Carolina are the top fuel cell states in the U.S. (U.S. DoE, 2014: 8). The common factors that have facilitated the development of the fuel cell industry in these states are directly related to the triple-helix model, and this provides a clear example of how these collaborations may enable the development or sustainability of a fuel cell industry.

In terms of the triple-helix model, government entities need to play a key role. Firstly, state economic development agencies must believe that the state has the capabilities to innovate around technology that may lead to patents and new products (U.S. DoE, 2014: 8). In the case of fuel cell development, the state energy and environmental agencies of these four states sought to reduce greenhouse gas and other polluting emissions and improve grid energy security (U.S. DoE, 2014: 8).

In the U.S., state energy and environmental agencies are often home to funding programmes that help facilitate demonstrations and early-market deployments of new and innovative energy technologies such as fuel cells. State lawmakers were also identified as key, as they can set state emission reduction goals to promote low-emission energy technologies and reduce the impact of various interruptions to the energy grid; create and fund renewable-energy and business development programmes; and devise tax incentives for fuel cell and hydrogen technologies (U.S. DoE, 2014: 8). State governors were also highlighted as having to set the stage for state efforts. An example would be the governors from eight states who agreed to a new initiative to put 3,3 million zero-emission vehicles (including fuel cells) on their roadways by 2025 (U.S. DoE, 2014: 8). The above emphasises the importance of government in supporting the development of a fuel cell industry through funding, policies, regulations and tax incentives.

Regarding the role played by universities, it was emphasised that, key in the abovementioned four top fuel cell states, were the presence of researchers at state universities, laboratories and established industries to drive fuel cell innovation and product development continuously (U.S. DoE, 2014: 8). The states all recognised the important role played by industry to ensure the product continuously evolve within the regional, state, national or international fuel cell industry (U.S. DoE, 2014: 8). Industry does not only mean fuel cell manufacturers, but also suppliers of equipment and material, and installers and developers of fueling infrastructure (U.S. DoE, 2014: 8).

All four states emphasised the importance of key partnerships between government, industry and universities (triple-helix spheres), working together on education and outreach, on developing vision plans and roadmaps, and on representing and promoting the state's fuel cell industry. Finally, there needs to be willing customers who seek to achieve sustainability goals by purchasing renewable energy and reducing emissions while ensuring reliable power (U.S. DoE, 2014: 8). The common denominators for developing and sustaining a fuel cell industry seem to indicate collaboration and coordination between the triple-helix spheres.

The above has illustrated the necessity of government funding support through grants, loans, tax incentives and supportive policies that encourage the development and deployment of fuel cells; the importance of incentives for the fuel-cell-related industry to conduct research; and the requirement that universities conduct research and develop the necessary skill sets as informed by industry. The discussion may serve as a practical example for the development of a fuel cell industry in South Africa.

4.6.2 Fuel cell industry Japan

Fuel cell technology and systems are not new to Japan. The first systems were set up at the prime minister's official residence in 2005 and commercial sales began in 2009 (Watanabe, 2014: 1). However, during the earlier years Japan's main focus was on nuclear power and not so much on hydrogen and fuel cells, until the Fukushima-Daiichi Nuclear Power Plant disaster occurred. In April 2014, around three years after the disaster, the Japanese government produced their fourth Strategic Energy Plan (SEP), with the objective that hydrogen will have a central role in Japan's energy future as it is seen as a more promising technology (Hydrogen London, 2014: 8; Maeda, 2003: 3). With this shift in focus, Japan's goal is to create a hydrogen society with vehicles, homes and businesses that are powered by fuel cells (U.S. DoE, 2014: 21). Although Japan is involved in various markets for fuel cell technology, their focus is on residential stationary power sources such as micro-CHP and transport (FCEV/ hydrogen refuelling stations), and fuel cell development is seen as critical for maintaining international competitiveness (Hydrogen London, 2014: 5; Maeda, 2003: 6).

To introduce and expand hydrogen and fuel cell technologies in the country Japan's Ministry of Economy, Trade and Industry released a Hydrogen/Fuel Cell Strategy Roadmap, outlining three phases (U.S. DoE, 2014: 31). The first phase entails increasing residential fuel cell units in Japan to 1,4 million by 2020 and 5,3 million by 2030; increasing the number of hydrogen stations for FCEVs to 100 in 2015; and commercialising FCEVs in 2015, fuel cell buses in 2016, and commercial/industrial fuel cell systems using SOFCs in 2017 (U.S. DoE, 2014: 31). The second phase entails the introduction of a hydrogen-based power generation on a full scale and the establishment of large-scale hydrogen supply systems between 2015 and 2030 (U.S. DoE, 2014: 31). The third phase entails achieving full-scale production, transportation and storage of hydrogen without emitting carbon dioxide, using carbon capture and storage by 2040 (U.S. DoE, 2014: 31). By the end of 2014 Japan had become global leaders in the transport infrastructure market by completing 41 hydrogen refuelling stations in planning, in addition to their existing 13 (Hydrogen London, 2014: 2). Japan has also managed to become a leader in "cutting-edge hydrogen technology and holds the largest share of patents in this field" (Fuel Cells Works, 2015: 1). However, due to the high cost of these technologies (possibly due to Japan relying on imports for its supply of natural resources), sales are slow and Japanese manufacturers are therefore continuously working on making devices smaller and cheaper (Watanabe, 2014: 1).

Japan's Ene-Farm programme is used as an umbrella term for the different micro-CHP fuel cell systems for residential applications across the country (E4Tech, 2015: 25). The programme is quoted as being the most successful fuel cell commercialisation programme in the world, having supported over 120 000 residential fuel cell units (Rose, 2015: 1). The programme, supported by an extensive government subsidy, was commercially launched in 2009 after a successful large-scale demonstration programme that started in 2005 (totaling up to 3 300 units) (Rose, 2015: 1; Fuel Cell Today, 2013: 1). Japan's government is a big supporter of the Ene-Farm programme and its main aim is for fuel cells to become cost-competitive on their own (Fuel Cell Today, 2013: 1). As such, the Ene-Farm programme is a public–private partnership, with government having agreed in 2009 to pay ¥1,4 million per unit, or up to half the unit cost, with a multi-year commitment entailing a declining subsidy per unit, but an increasing overall budget (Rose, 2015: 1). Current indications are that it will now run through to 2019, and 2017 was seen as the year for the market launch of a number of 5 kW to 50 kW fuel cell system. The country was also expected to add more proton exchange membrane (PEM) and SOFC micro-CHP fuel cell systems in 2017 with the support of the Ene-Farm programme (E4Tech, 2015: 15).

A primary focus of technology developers has been reducing the cost, increasing the efficiency and making it possible to offer a range of units to customers, providing differing levels of hot water and electricity to suit differing residential requirements (Fuel Cell Today, 2013: 1; E4Tech, 2015: 25). These systems are continuously evolving through the use of fewer components and increased economies of scale (Fuel Cell Today, 2013: 1). Toshiba and Panasonic, both lead producers of fuel cells, have improved their offerings on a regular basis since 2009 (E4Tech, 2015: 25). According to Panasonic they have made their Ene-Farms cheaper by refining the design to use fewer and smaller components, and are endeavouring to reduce the size further; they have, however, not provided any details on how this would be done (Watanabe, 2015: 1; Rose, 2015: 1). In addition, the New Energy and Industrial Technology Development Organisation (NEDO) actively takes part in fuel cell technology development; in the case of the Ene-Farm programme it focuses on cost reduction and improved durability and performance (Okawara, 2011: 7).

The NEDO receives funding from government and disperses it as grants for universities and subsidies for private companies for R&D purposes (Okawara, 2011: 7). In the context of Japan's Ene-Farm programme there has clearly been active relationships between the triple-helix spheres, with each playing a key role: government supports R&D initiatives through funding; the R&D activities consist of research done by university, industry and public research councils, managed by NEDO (universities); and companies participate in the development and early deployment of the technology. Although a number of companies were initially involved in this process, the main participants today are Panasonic and Toshiba, offering PEM units, and Aisin Seiki, offering SOFC units (industry) (Rose, 2015: 1). The Ene-Farm programme is therefore an example of how public–private partnerships and triple-helix dynamics may push new technology into the marketplace (Rose, 2015: 1).

Japan has various colleges and universities that offer fuel cell technology programmes and research activities. At the Daido University the Fuel Cell Research Centre has around 40 researchers, assistant researchers, graduates and undergraduate students who are actively engaged in research on low- and high-temperature PEMFC (Daido University, 2017: 1). Additional research programmes for innovation breakthroughs in Japan include the Advanced Fundamental Research on Hydrogen Storage Materials, named Hydrogenius, which is based at Kyushu University; the Polymer Electrolyte Fuel Cell Cutting-edge Research Centre at the National Institute of Advanced Industrial Science and Technology; and the Research Centre for Hydrogen Industrial use and Storage called Hydro Star (Akiba, 2010: 15; FCPO, n.d.: 12).

The University of Yamanashi's Department of Engineering hosts a programme called the Advanced Education Programme for International Fuel Cell Engineers, of which the purpose is to "train technological researchers in fuel cell engineering who can conduct the most advanced research in the future and be active internationally" (University of Yamanashi, n.d.). The programme consists of three unique curricula, namely the "synchronised fuel cell education" programme that covers basic and practical science, the international practical education programme and the learnership training education programme (University of Yamanashi, n.d.; Akiba, 2010: 15). This initiative is a collaboration between three universities and six companies, with the goal of developing human resources to lead the way in this green-energy area, coping with the hydrogen economy with full-fledged fuel cell technology, through active participation in joint research activities among industry, government and academia (Akiba, 2010: 15; University of Yamanashi, 2016: 2). This indicates their acknowledgement of the importance of triple-helix dynamics for the fuel cell industry in their country and their continuous endeavours to ensure that these collaborations take place.

4.6.3 Fuel cell industry in Germany

Despite Europe's technology capability, there are only a limited number of larger stationary fuel cell systems that have been implemented, with merely hundreds of micro-CHP units (E4Tech, 2015: 25). Supporting the European fuel cell industry is Europe's Fuel Cell and Hydrogen Joint Undertaking (FCH2JU), also supported by various national governments, notably Germany, which until now has remained small in comparison to the global leaders (E4Tech, 2015: 25). Germany has announced its new funding initiative for fuel cell CHP, which is similar to the Ene-Farm programme. This, coupled with its continued support for the National Organisation Hydrogen and Fuel Cell Technology (NOW GmbH) and the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP), makes it still an important fuel cell supporter (E4tech, 2016: 8).

In 2000, Germany accepted the Renewable Energy Source Act (Erneuerbare Energien Gesetz), which established fixed feed-in-tariffs for renewable energy and gave renewable sources grid priority (Leipold, 2014: 1). The country has become a front-runner in renewable-energy development and has gone through an ambitious energy transition through the Energiewende project, seeking to switch the country's entire energy supply to renewable energy and to become increasingly energy efficient (CEW, 2017: 1). The project seeks to reduce greenhouse gas emissions by up to 40% by 2020, by up to 20% by 2040, and by up to 80% by 2050, compared with the 1990 base year (Leipold, 2014: 1; Bräutigam et al., 2015: 4). In 2015, renewable-energy sources were already producing up to 30% of the country's total consumed electricity and it is hoped that it will increase to 80% by 2050 (Bräutigam et al., 2015: 4). The country is also planning the gradual phasing out of all its nuclear power plants by 2023, thereby revolutionising its energy infrastructure (Bräutigam et al., 2015: 4).

Data from 2013 on fuel cell exports from Germany indicated that the country accounted for 60% of global fuel cell technology sales, highlighting the country as a key player in the industry (Leipold, 2014: 2). With fuel cell technology demand expected to increase substantially in various industries, Germany is increasingly advancing its fuel cell industry through funding and R&D efforts (Leipold, 2014: 2). With around 300 Germany companies planning to invest in the promotion and expansion of a nationwide hydrogen infrastructure to ensure a sustainable and secure economy, it places the country in an economically advantaged position (Bräutigam et al., 2015: 4). In addition, the German Engineering Federation expects at least 70 000 fuel cell heating systems to be ready for installation by 2020, with the same volume to be ready for export (Leipold, 2014: 4).

To meet the abovementioned targets the country requires extensive manufacturing capacity, to be achieved through the collaboration and support of numerous companies located in the German fuel cell industry. According to a presentation by the U.S. Department of Commerce released in 2015, Germany had more than 100 fuel cell suppliers at that stage, with more than 65 institutions doing research in the industry (U.S. Department of Commerce, 2015). The Verband Deutscher Maschinen- und Anlagenbau, a German engineering association, indicated 22 fuel cell system manufacturing companies, 47 fuel cell component manufacturing companies and 10 specialised fuel cell R&D institutes as members of the association (Leipold, 2014: 8). These entities are typically known to manufacture stack components, periphery, reformers, electrical power supply, early and special market and inverted rectifiers (Leipold, 2014: 8). Through the continuous collaboration by companies to advance the fuel cell industry in Germany, the country has the capacity to sustain an economically advanced fuel cell industry, to remain one of the front-runners in the industry and to serve as an example to countries such as South Africa who are still developing the industry. Below are key fuel cell projects and initiatives in Germany that highlight active triple-helix relationships.

NOW GmbH ensures the implementation of two federal developments programmes, one of them being the NIP (Leipold, 2014: 5). The objective of these programmes is to ensure market preparation of alternative drive technologies along with efficiency and storage technologies, and include R&D projects to test these technologies under everyday conditions (Leipold, 2014: 5). NOW GmbH acts as an interface between government and partners from research and industry, which is indicative of triple-helix dynamics. Further supporting the importance of triple-helix relationships within the fuel cell industry on an international scale is the establishment of the NIP. The NIP provides a common framework for several hydrogen and fuel cell research projects conducted by academic institutions and industry, and was implemented in 2006 in an attempt by government, industry and R&D institutes to speed up the process of market entry of products (Leipold, 2014: 16). The NIP strategy is divided into four programme areas, namely transport and hydrogen infrastructure, hydrogen provision, stationary-energy supply and early/special markets. The programmes ensure the equal advancement of numerous hydrogen and fuel cell technology product and application options, and address in a targeted way the market-specific challenges of market preparation (Leipold, 2014: 5).

In 2016 phase two of the NIP (NIP II), with funding of approximately €1,4 billion over 10 years, was approved. The first NIP ran from 2005 to 2006, with a budget of €700 million for R&D activities to bring technologies to market readiness, and supported demonstrations in the Callux project (E4Tech, 2015: 25). NIP II remains jointly funded by several German federal ministries and will mainly focus on road transport, hydrogen infrastructure and stationary fuel cells at residential, commercial and utility scale (E4Tech, 2015: 25). The objective of this programme is to promote collaborations between small and medium-sized enterprises (SMEs), with applied and fundamental research (E4Tech, 2015: 25).

The FCH2JU in itself is an example of triple-helix partnerships, as it is the result of long-standing cooperation between representatives of industry, the scientific community, public authorities, technology users and civil society in the context of the European Hydrogen and Fuel Cell Technology Platform (FCH, 2017: 1). It is a public–private partnership that supports research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. The FCH2JU is made up of three members, namely the European Commission representing government, Hydrogen Europe representing fuel cell and hydrogen industries and the Research Grouping N.ERGHY representing the research community (FCH, 2017: 1).

Germany's Ene-Field is another example of triple-helix dynamic taking place in the German fuel cell industry. The Ene-Field is the largest European demonstration of the latest smart-energy solution for private-home fuel cell micro-CHP and aims to deploy around 1 000 fuel cell heating systems in eight key European member states (FCH, 2016: 4). The project duration is five years, with demonstrations for two to three years. It is co-funded by the FCH2JU with 26 partners involved, which include leading European fuel cell micro-CHP developers, leading European utilities, leading research institutes, and partners in charge of dissemination and coordination of the project (FCH, 2016: 4). In essence, the varied partners involved in the project include manufacturers, industry and research institutes, which include universities and government entities such as the European Commission, thereby highlighting triple-helix relationships within the project. The FCH2JU is committing €26 million to the project under the EU's 7th Framework Programme for funding research and development (FCH, 2016: 4; E4tech, 2016: 24).

In Germany, at both national and state level, support is available for CHP and particularly for fuel cell micro-CHP (E4Tech, 2014: 27). Germany's Callux programme, launched in 2008 together with partners from industry and supported by the German Federal Ministry of Transport and Digital Infrastructure, is the country's biggest field test project for small residential fuel-cell-based heating systems (Ene-Field, 2017: 1). As part of the national innovation programme for hydrogen and fuel cell technology, coordinated by NOW GmbH, the industry, together with the abovementioned ministry, is investing €75 million in promoting the use of fuel cell technology (Ene-Field, 2017: 1). Partners that form part of this initiative include three system manufacturers and five utility companies, and at project level it is coordinated by the Centre for Solar Energy and Hydrogen Research (Ene-Field, 2017: 1).

Although the German government provides funding for R&D in fuel cell technology, the fuel cell market is characterised by cost-intensive products, and as the cost is difficult to give through to the end-user, more funding is needed to advance these technologies (Leipold, 2014: 16; Bräutigam et al., 2015: 4). There are more than 65 research institutes in Germany active in the fuel cell technology field, mainly forming part of universities (Schiel, 2010: 9; Leipold, 2014: 16; GTAI, 2013: 1). Fuel Cell Energy Solutions (FCES) based in Germany, received nearly €5 million from the Federal Ministry for Economic Affairs and Energy to support a three-year R&D project between FCES and partner Fraunhofer Institute for Ceramic Technologies and Systems (U.S. DoE, 2014: 41). Germany furthermore has a few training institutions that offer short courses on fuel cell technology ranging from one to five days. These include Haus der Technik, TÜV SÜD Akademie GmbH and Weiterbildungszentrum für innovative Energietechnologien der Handwerkskammer Ulm (HyFacts, n.d.).

Universities in Germany offering courses in the fuel cell sector include Karlsruhe Institute of Technology, Ruhr University, Saarland University, University of Stuttgart, Technical University Berlin, Technical University Hamburg, University of Bayreuth, University of Duisburg, University of Freiburg, Technical University Berlin, University of Kassel, Institute for Energy and Environmental Chemical Engineering, Institute for Chemical Process Engineering, University of Applied Science Hamburg, University of Applied Science Stralsund, University of Regensburg and the University of Ulm among others (Wagner, n.d.: 2). The Callux programme has incorporated fuel cells into vocational training, has trained technicians in the practical test, and has developed training material such as the online information programme (Ene-Field, 2017: 1; Wagner, n.d.: 2).

Non-universities research centres include the Centre for Fuel Cell Technology GmbH Duisburg, Zentrum für Sonnenenergie- und Wasserstoffforschung, Research Institute for Energy Economy, Institute for Future Energy Systems Saarbrücken, Ludwig-Bölkow-Systemtechnik, Institute for Micro Technology Mainz and Karl-Winnacker Institute (Wagner, n.d.: 2). Among many research centres is the Research

Centre Karlsruhe and the Information Communication Technology Institute for Chemical Technology (Wagner, n.d.: 2). Although the fuel cell industry in Germany serves as a good example for countries at the developing stage of the fuel cell industry, it does face a number of challenges. These include the pace of the market potentially overtaking the slow legislation process, the need for reliable policies beyond existing ones such as the NIP, the availability of additional funding for R&D, the markets still being characterised by high-cost components, slow market acceptance resulting in a delay in mass use and some German energy giants being reluctant to invest in future-oriented technologies (U.S. Department of Commerce, 2015).

4.6.4 Fuel cell industry in South Korea

South Korea is putting in place favourable fuel cell policies and incentive structures that include a renewable portfolio standard. This standard requires power utilities generating more than 5 000 MW to generate at least 2% electricity from renewable resources in 2012, increased to around 3,5% in 2016, and to 10% in 2020 (Altenergymag, 2015: 1; E4Tech, 2014: 22). South Korean traditional utilities have begun to realise the attractiveness of fuel cell technology, even when compared with solar and wind energy, and the country's climate action plan is therefore to reduce its greenhouse gas emissions by 25% by 2020 and by 40% by 2030 (Hydrogen London, 2014: 9; Agnihotri, 2015: 1). South Korea also aims to derive around 11% of the country's energy from new renewable resources by 2035, while the country's capital, Seoul, is aiming to reach 50% of its renewable-electricity generation from fuel cells by 2030, achieved though government–industry partnerships (Altenergymag, 2015: 1; Agnihotri, 2015: 1).

Since 2008, 21 fuel cell sites have been installed in Korea, which contributes up to 115,6 MW of power available for homes and buildings (Hydrogen London, 2014: 9). In 2016 Hyundai and the Korean government announced its intent to replace up to 26 000 public-transport buses fuelled with compressed natural gas with fuel cell electric busses (E4Tech, 2014: 37). The recently introduced Renewable-heat Obligation also keeps utilities and other large energy users under pressure to adopt 'renewables', in this case also fuel cells in CHP mode (E4Tech, 2014: 22). With its new focus on fuel cell technology, South Korea has quickly emerged as one of the most attractive investment destinations for North American fuel cell manufacturers (Agnihotri, 2015: 1). In recent years South Korean companies have acquired fuel cell companies and established a manufacturing presence in the U.S.; they have also partnered with North American companies to export and manufacture systems to be installed in South Korea, which will help drive fuel cell production, job growth and technology (Altenergymag, 2015: 1).

Kyung-In Energy Development, established in 1969 and renamed as POSCO Energy in 2005, with its focus on fuel cell technology was seen as a perfect fit for the South Korean government's Creative Economy Policy, and was selected by the government as a "flagship project" that serves as a future growth engine (POSCO Energy, 2015: 9). Being a major investor in the stationary fuel cell sector, the company facilitated the country's production capability and the roll-out of larger-scale fuel cell system, which enabled South Korea to enter the fuel cell space (E4Tech, 2014: 27). Over the years POSCO Energy has installed over 154 MW of MCFC 300 kW and 2,5 MW systems in 20 locations, either as single units or in the form of fuel cell parks, and opened a 60-MW-grade fuel cell power complex in Hwaseong, Gyeonggi-do. (E4Tech, 2014: 27; POSCO Energy, 2015: 9). The company was planning on delivering a 100% locally manufactured fuel cell with the opening of a cell manufacturing facility in 2015 (POSCO Energy, 2015: 9). A slowdown for the South Korean fuel cell industry was, however, predicted for 2017 based on the sales for 2016 (E4Tech, 2014: 22).

Firstly, some of POSCO Energy's key fuel cell projects are situated in Seoul, with an installed capacity of 19,6 MW that is able to provide electricity for around 40 000 households. Secondly, there are projects in Incheon and Gyeonggi-do (called the Gyeonggi green-energy plant) with an installed capacity of 58,8 MW providing up to 70% of household electricity consumption and 10% of heat consumption in Hwaseong. The country proclaimed a high status for this plant as the world's largest operational fuel cell park for the stationary market in 2014 (Hydrogen London, 2014: 9; Overton, 2014: 1; POSCO Energy, 2015: 18). Thirdly, cited as the nation's first fuel cell installation case using biogas, is the project in Gyeongsang-do, with an installed capacity of 1,2 MW and using biogas at the Gangbyeon Office of Busan Environmental Corporation in Saha-gu, Busan. Finally, the fuel cell project in Gangwon-do has installed capacity of 0,3 MW at KOGAS in Samcheok, Gangwon-do (POSCO Energy, 2015: 18).

More recently, POSCO Energy has built a 360 MW fuel cell plant in the city of Pyeongtaek (Wonjung-ri), also in the Gyeonggi Province, which is planned for operation in 2018 and will supply heat to the Pyeongtaek Tourist Complex and the Poseung Industrial Complex (Overton, 2014: 1; Yeon-jin, 2014: 1). POSCO signed investment agreements with various entities, including Doosan, Korea Gas Corporation, Korea Investment and Securities, Darby Overseas Investment, and GK Holdings, stipulating that approximately ₩2 trillion is to be invested in the 140 000m^2-wide plant (Yeon-jin, 2014: 1). The Korea Gas Corporation will be responsible to supply fuel, POSCO Energy and Doosan will be in charge of the supply of fuel cell power generation equipment, Darby Overseas Investment and Korea Investment and Securities will finance and procure, and GK Holdings will oversee the project (Yeon-jin, 2014: 1). The project is envisioned not only to attract major foreign investment, but will also create around 500 new jobs (Hydrogen London, 2014: 9; Tracy, 2016: 2).

There are various initiatives and collaborative efforts between government, industry and university/research centres that indicate triple-helix dynamics within these projects. As regards the South Korean government, policies continually support the further expansion of fuel cell unit numbers and foreign manufacturers of fuel cells is subsidised through a R&D tax credit programme that reduces import duties on equipment by 50% (Tracy, 2016: 1; E4Tech, 2014: 22). POSCO Energy actively responds to government's policy on increasing the supply of renewable energy through advancing the renewable-energy business such as photovoltaic power, wind power, and fuel cells and adhering to the requirements regarding the renewable portfolio standards (POSCO, 2015: 9). There is a fuel cell industry vitalisation forum that comprises politicians, academics and subject matter experts for justification of government subsidy, which indicated strong triple-helix dynamics (POSCO, 2015: 28).

4.7 Summary

This thesis argues that South Africa needs to utilise its natural minerals, specifically platinum, by developing a local fuel cell industry, possibly through triple-helix dynamics. By comparing the advantages and disadvantages of fuel cells with competing technologies power technologies, the chapter argues in favour of fuel cells, as they provide a distinct advantage over current energy generation technologies such as batteries, solar-powered devices and wind turbines - from their high efficiency to their scalability. Through the discussion on fuel cells in the global context, the chapter sought to emphasise how triple-helix dynamics facilitated the development of a fuel cell industry in countries considered to be leaders in the field. It seems clear through the global literature and discussions in this chapter that key elements needed for South Africa to develop a successful and sustainable globally competitive fuel cell industry include, among others, funding mechanisms, fuel cell training institutions, adequate policy development and support, as well as the adequate implementation of such policies.

CHAPTER 5: THE FUEL CELL INDUSTRY IN SOUTH AFRICA

The aim of this chapter is to provide an overview of the current fuel cell industry in South Africa. The chapter starts with a discussion on the history and current trends of manufacturing in South Africa, followed by the history and current trends of platinum in South Africa. This is crucial for understanding the context in which the fuel cell industry falls, as it is linked to the South African manufacturing and platinum industry. Following this is a section on the fuel cell industry in South Africa. This section looks at the Green Economy, as fuel cells are a green technology; the fuel cell market in South Africa; the advantages and challenges of fuel cell development in South Africa; and the current state of the fuel cell industry in the country. This section provides examples of fuel cell activities where triple-helix dynamics are present. Specific focus is placed on the Hydrogen South Africa (HySA) programme, which forms the case study for this thesis and is the essence of what triple-helix collaborations are all about.

5.1 History and current trends of manufacturing in SA

Before the South African manufacturing industry became most productive in the mid-20th century (Verhoef, 1998: 20), it was entirely derived from agriculture and intended mainly for the domestic market. As the mining industry sector expanded, new industries emerged (Photius.com, 2004: 1; Verhoef, 1998: 17). The country was heavily dependent on imports, ranging from mining equipment to textiles and clothing until the 1920s, when the government started encouraging local manufacturing (Verhoef, 1998: 22). This was done through establishing state corporations to produce electricity and steel for manufacturers' use, with tariffs designed to protect the local industry (Photius.com, 2004: 1; Verhoef, 1998: 22).

The manufacturing industry steadily grew from 1936, with dramatic growth after 1948 continuing until the early 1950s. Since that time the local iron and steel industry were the key drivers for the manufacturing industry until the early 1990s, when the manufacturing sector became more diverse (Photius.com, 2004: 1; Tregenna, 2007: 27). The South African manufacturing sector became increasingly capital-intensive, despite the availability of a large labour pool in the country, with government encouraging capitalisation through tax incentives through state corporations (Photius.com, 2004: 1).

As manufacturing enterprises gradually increased their fixed-capital stock during the 1970s, it led to surplus capacity by the mid-1980s (Photius.com, 2004: 1). Examples of this include the massive extensions at Eskom and the establishment of Sasol synthetic fuel plants as well as the Koeberg nuclear power station, demonstrating significant capital intensification with a limited labour requirement (Photius.com, 2004: 1; Verhoef, 1998: 27; Black and Hasson, 2012: 4).

Private manufacturers shifted towards machinery and technology, looking to reduce labour costs to compete globally and avoid confrontations with an increasingly volatile labour force (Photius.com, 2004: 1). However, in the mid-1980s it was realised that the manufacturing sector would be the primary job-creating sector in the country and as such government programmes in the 1990s started encouraging more labour-intensive manufacturing enterprises (Photius.com, 2004: 1; Verhoef, 1998: 30).

In the 1980s the country experienced a general economic downturn, chronic high inflation and a debt crisis, causing a slump in manufacturing output during the decade, with the textile, footwear, industrial chemical and non-ferrous base-metal industries suffering most (Photius.com, 2004: 1; Sunjka and Emeanu, 2015: 193). However, after 1990 manufacturing sales increased (contributing more than 22% of total economic output), mostly attributed to improved business and investor confidence, increased domestic and export sales, and a decline in stocks of finished goods (Photius.com, 2004: 1).

During the 2009 global financial crisis South Africa’s manufacturing sector experienced a severe contraction that resulted in more than 200 000 job losses in the sector, and it still has not recovered (SEDA, 2012: 19; Manufacturing circle, n.d.: 2; Sunjka and Emeanu, 2015: 193). As the manufacturing sector was struggling to recover from the financial crisis, the sector was hit by a further recession in 2016, which lasted for three quarters, further straining its recovery. The South Africa manufacturing sector contributed about 12% to the country’s gross domestic product (GDP) in 2016 and 13% in 2017; however, the industry has remained fragile and continuously struggles to shed de-industrialisation (Oliveira, 2017: 1; StatsSA, 2017: 12).

Although there has been a major shift in the manufacturing industry towards embracing the latest technological and digital advances (merSETA SSP, 2016: II; 2), the industry is still regarded as a major job-creating sector according to the National Development Plan (NDP), National Growth Plan (NGP) and Industrial Policy Action Plan (IPAP), and remains critically important for growth in South Africa (merSETA SSP, 2016: 14; Tregenna, 2007: 27). Manufacturing is among the top three multiplier sectors in terms of value addition and export earnings, and provides the only viable means of beneficiating South African natural resources (Manufacturing circle, n.d.: 2).

5.2 History and status of platinum in South Africa

In 1924 the first platinum nuggets were discovered in South Africa, which led to follow-up work by a geologist named Hans Merensky, who discovered two deposits of 100 km each in length (Chamber of Mines, 2017: 1; IDC, 2013: 3). This became known as the Bushveld Igneous Complex (Chamber of Mines, 2017: 1). The Merensky reef stretches from southern Zimbabwe through to the Rustenburg and Pretoria regions and is the centre of platinum mining in South Africa, hosting companies such as the Rustenburg Platinum and Bafokeng Rasimone Platinum Mines (RSA, 2017: 1). In 1925 the eastern limb of the Bushveld Igneous Complex was discovered, and for many years this has produced more that 75% of the world's supply (Chamber of Mines, 2017: 1).

Since the Second World War, platinum mine production grew continuously in response to the development of new applications for platinum metals (Chamber of Mines, 2017: 1). In the 1960s there was a growing demand for platinum jewellery and it was in the early 1990s that the platinum mining industry really took off (Chamber of Mines, 2017: 1). Platinum replaced gold as the country's primary contributor to GDP and was stimulated, to a large extent, by the increase in global demand for catalytic converters in the automotive industry (Jansen, 2016: 18). By the end of the 20th century the platinum sector was dominated by Gencor, JCI and Lonrho. The mines in these groups were eventually housed under Impala Platinum (Implats), Anglo American Platinum (Amplats) and Lonmin respectively, the three largest platinum group metal suppliers in the world (Chamber of Mines, 2017: 1; Bowman and Isaacs, 2014: 4).

The platinum industry (with the rising price of platinum and other platinum group metals) made major profits during the global commodities boom of the period 2000 to 2008, just before the global economic crisis in 2009 (Bowman and Isaacs, 2014: 9). Subsequently, the platinum price returned to around precrisis levels, with experts having foreseen an increase in platinum prices in the medium to long-term (Bowman and Isaacs, 2014: 9). However, it was reported that the profits of the abovementioned three major platinum producers continued to fall due to the increased costs of production (specifically labour costs), which continued to rise throughout the crisis (Bowman and Isaacs, 2014: 10). Factors such as the uncertainty around the price of platinum, global demand conditions, ore grades and cost of production cast doubt on whether a 2000–2008 boom can be repeated (Bowman and Isaacs, 2014: 10).

The South African platinum industry is interlinked with the mining industry (still a major source of employment), as it is through mining that platinum is retrieved in its raw form for beneficiation purposes (DMR, 2014: 7). A key factor continuously threatening the sustainability of the South African mining industry is the continuous strikes by miners. This poses challenges for the South African mining industry as a whole, also for platinum mining, which is the focus of this study. In an attempt to reduce the effects of this ever-present threat, mine mechanisation is increasingly becoming an attractive alternative for owners of mining corporations (Bowman and Isaacs, 2014: 33).

However, mechanisation may not always be the solution, as many commentators suggest that, in many areas, existing geological conditions present major technological obstacles that render the implementation of mechanisation not as viable as perceived (Bowman and Isaacs, 2014: 5). Mechanisation refers to "any machine, process or activity that reduces human effort required to break or move rock or material in a mine" (Willis et al., 2004: 117).

In addition to technological obstacles for mechanisation and mine strikes, there are also other key factors that affect the platinum mining industry in South Africa, such as access to platinum-bearing land and the price of platinum. These factors are discussed in short below.

5.2.1 Labour strikes

The South African mining industry has long faced ongoing strikes by miners seeking better working and employment conditions, a situation that has continued into the 21st century. These strikes often lead to volatile and violent situations, as was evident with the Marikana tragedy in 2012, where 34 miners were shot and killed on Wonderkop in the North-West province of South Africa (Marinovich, 2012: 1). In the period 2013 to 2014 the three major world players Amplats, Implats and Lonmin closed their mining operations in Rustenburg in an attempt to restore profits lost through labour strikes, resulting in around 7 500 job losses (Seccombe and Maswanganyi, 2014: 1).

On 23 January 2012 around 70 000 workers at South Africa's three largest platinum mines began a strike for higher wages (Bowman and Isaacs, 2014: 5). These Association of Mineworkers and Construction Union (AMCU) members went on strike for a basic wage of R12 500 per month for entry-level workers. This amount was more than double the current wage for these workers at the time (Kantor, 2013: 1). Mining companies had warned that these demands would destroy the industry as the higher wages were not in sync with the expected lower-profit rates and reduced growth in the industry at that time (Kantor, 2013: 1; Bowman and Isaacs, 2014: 34). As such, the actions of the AMCU members were written off by mine owners as irresponsible, greedy and unrealistic (Bowman and Isaacs, 2014: 4).

In the past, South African mines were able to employ a large workforce due to the low cost of labour (Taylor, 2013: 1). However, with the strikes and demand for higher wages constantly increasing, employers argue that it is impossible to maintain the same level of labour absorption in the mining industry going forward, with major job losses therefore on the horizon (Bowman and Isaacs, 2014: 36). A local fuel cell industry may alleviate this through the creation of job opportunities, if successfully developed through a triple-helix dynamic facilitating university, industry and government collaboration.

5.2.2 Mechanisation

As mentioned earlier, mechanisation has been seen by mine owners as an attractive possibility to deal with labour conflicts and ensure the sustainability of the mining industry. However, there are contesting views on the possible effect of mechanisation on the South African mining industry. On the one hand it is seen in a negative light in the face of South Africa's skills shortage and increasing unemployment rate. South Africa has the abundance of workers that traditional mining operations required. If mechanisation is implemented at all mines, there would be extreme job losses (Taylor, 2013: 1). It would also be a direct barrier to the ideal of the beneficiation initiative, which is to create more jobs and boost economic growth. A more optimistic view on mechanisation is that, if implemented, it could provide opportunities to redirect labour into other forms of work and other industries. For example, workers previously employed at these platinum mines could be absorbed into the fuel cell industry due to their experience in the platinum mining industry. It is also a way to save on costs as it has been estimated that mechanised mining costs approximately 40% less than non-mechanised conventional mining methods (Palladium Alliance International, 2012: 1).

Platinum mines Lonmin and Booysendal are good examples of varying outcomes of mine mechanisation. From 2000 to 2008 Lonmin attempted to mechanise several of its shafts in an effort to insulate the company from the threat of wage inflation and safety-related expenses (Bowman and Isaacs, 2014: 33). However, the company was restructured to boost shareholder value due to a failed takeover bid by Xstrata in September 2008 (Bowman and Isaacs, 2014: 33). As the company started focusing on closing loss-making operations, Lonmin scaled back on the mechanisation initiative to cut costs and the three new Marikana shafts, Saffy, Hossy and K4, targeted for mechanisation were converted to hybrid systems using labour after difficulties in containing costs (Bowman and Isaacs, 2014: 33). Furthermore, as the mechanisation equipment was designed and developed by a Swedish company, challenges encountered included that the equipment was unsuited to the complex geology. It was also unreliable, spare parts were expensive to maintain and source, and the equipment was mismatched with the skills levels of the workforce (Bowman and Isaacs, 2014: 33). This illustrates that, although mechanisation is likely to be pursued successfully in some areas where geographical conditions allow, there are still many key areas that pose serious problems for the implementation thereof.

At the Booysendal Platinum Mine, situated on the border between Limpopo and Mpumalanga, attempts to mechanise have been more successful. At this mine only a fraction of the labour of traditional mining operations is used and new technologies used here require higher skill levels to keep mechanised fleets running and to manage mechanised mining operations (CMMS, 2014: 1). This is highlighted as Booysendal claims that it takes 1 500 people to mine around two-hundred thousand tons at its mine, compared with the 5 500 to 6 000 people it would usually take to do the same in a conventional mine (Hartley, 2014: 1).

As higher skill levels are required, workers are paid more and fewer workers are required, thereby reducing the possibility of strikes, which may be a main incentive for employers to implement mine mechanisation on a large scale (Willis et al., 2004: 117). Interestingly, these workers – employed as machine operators – all earn above R12 500 on a monthly basis; the amount which was demanded through strikes for deep-level miners in 2012 (Hartley, 2014: 1). It seems therefore that, when using a smaller labour force with higher skill sets in a mechanised mine, the operations are far more sustainable and reliable than in the case of a large labour force in a traditional mining environment. It has also been found that employment in more highly skilled occupations are associated with lower rates of crime (Toner, 2011: 59). As such, introducing large-scale mechanisation in mines is beneficial for mining companies, but not for workers seeking employment, and although it might improve worker safety, increase productivity and sustainability and reduce direct costs, the number of job opportunities offered will be against the aspirations of South Africa to create more employment for its people (CMMS, 2014: 1; Taylor, 2013: 1).

5.2.3 Access to platinum-bearing land

Another difficulty in the mining industry, and specifically in platinum mining, is the matter of access to land, as platinum-rich land is often privately owned, as in the case of the Bafokeng region. The Bafokeng Tribal Kingdom is located on platinum-bearing land, which could have been problematic should the tribe people have refused mining companies access to the land. However, through the joint venture between Amplats and Royal Bafokeng Holdings, known as the Bafokeng Rasimone Platinum Mine Joint Venture (BRPM JV), platinum concentrate is produced and then sent to Amplats for value-adding (beneficiation) in its refineries (RBP, 2015: 1). The BRPM JV operates at the western limb of the Bushveld Igneous Complex near Rustenburg, where the only major shallow platinum group metals (PGMs) reserves are still available for mining in South Africa (RBP, 2015: 1). Royal Bofokeng Platinum Limited are also developing a new mechanised underground mine, which is expected to reach a steady state by the first quarter of 2019 (RBP, 2015: 1).

5.2.4 Price of platinum

The raw-material pricing of monopolistic suppliers is also an ongoing problem for South African manufacturing firms. South Africa imports final platinum products on a global scale and as the rand is weaker compared with the currencies of many other countries, we pay much more for products made overseas than we would if the products were manufactured locally (with our platinum resources). This undermines local producers, as they cannot achieve international competitiveness (merSETA, 2013: 49). Mining houses also charge local manufacturers the same price at which the product would be sold abroad, despite the fact that it need not be transported abroad, nor have export and import taxes levied on it (Bowman and Isaacs, 2014: 34).

In view of the above there are clearly many factors possibly constraining the local beneficiation of metals, with strikes and labour unrest, mechanisation and retrenchments, access to platinum-bearing land and the price of local raw minerals, being only a few. However, despite serious challenges facing the South African mining industry, the country is still the world's leader in producing PGMs (IDC, 2013: 3). Additionally, the wide-scale adoption and commercialisation of fuel cell technologies potentially provide a new growth phase in PGM demand (IDC, 2013: 3).

5.3 Platinum beneficiation in South Africa

As mentioned, the bulk of PGMs is currently mined in South Africa in raw concentrate form and thereafter partially beneficiated within the country through smelting and refining processes in preparation for exportation (Soko and Balchin, 2012: 9). This means that the final product is again imported by South Africa, which negatively impacts our economy, mainly due to the high price of imported manufactured goods such as catalytic converters, as trade is subject to international tariffs. South Africa therefore has no competitive advantage in this regard and should gain from establishing sustainable metal beneficiation industries in the country to manufacture products such as fuel cells locally (Dewar, 2012: 2).

Precious-metal products such as platinum products are generally available across the world at internationally set prices. These platinum products are mostly manufactured or beneficiated in countries with limited to no mine extraction of these metals, such as China and the U.S. Most of the world's mineral beneficiation companies are located in developed countries, so that they can supply to an already well-established consumer market (Mining Weekly, 2013: 1). South Africa is an example of a country with an already established consumer market for products produced in developed countries that import metals from metal-rich countries such as South Africa and Russia and then manufacture consumer products.

Although South Africa is the largest platinum producer in the world, it does not feature on the list of countries with a significant demand for platinum (Van der Merwe, 2007: 1). The areas that dominate this list include Europe, North America, Japan and China, with their enormous capacity for manufacturing (Van der Merwe, 2007: 1; Statista, 2010: 1). The successful establishment of an infrastructure able to manufacture and produce fuel cells in South Africa should increase the country's demand for platinum in the long-term.

5.3.1 Beneficiation linkages

A general definition of "beneficiation" or "value-added processing" is that it involves transformation of a primary material (produced by mining and extraction processes) to a more finished product with a higher sales value (Robinson and van Belowt, 1990: 91). However, beneficiation is a dynamic concept and within the broad concept of beneficiation there are various interconnected subsectors, of which downstream beneficiation, upstream beneficiation, and various linkages are just a few.

Downstream beneficiation (or downstream linkages) refers to the idea of natural-resource-producing countries, such as South Africa, processing/transforming raw materials locally (using local resources such as labour and capital) into a more finished product that has a higher value than the sale of the raw materials for export (Columbia University, n.d.: 1). Because so much of the developed world outsources its manufacturing capabilities to developing countries, it is believed that downstream, local beneficiation in South Africa would be a catalyst for creating jobs, enhancing skills and diversifying the economy (Columbia University, n.d.: 1). It has been suggested that exporting raw materials is equivalent to importing poverty, referring to the fact that, by not beneficiating products locally, we are hampering job creation and therefore adding to the already out-of-control unemployment rate in South Africa (Van der Merwe, 2007: 1).

As South Africa imports a variety of finished products from countries in the developed world, it has led government to frown upon the comparative lack of mineral processing/beneficiation taking place in South Africa. It is seen as a significant loss in export revenue and employment creation opportunities (Soko and Balchin 2012: 9). The government has therefore targeted the mineral beneficiation industry as a growth sector and, where industrial opportunities exist, some downstream beneficiation is already taking place (IMA, 2013: 1).

Although this is the case, the beneficiation policy, which supports downstream beneficiation, has not been received well by the resources sector, as it claims that the sector's expertise lies in mining, not in manufacturing (Mathews, 2013). This could act as a barrier to the attempted introduction of beneficiation in various industries. The resistance is corroborated by Stilwell (2004), who states that the proposal to compel mining companies to beneficiate or add value to raw materials is misguided: "South African mining houses have completed a decades' long process of unbundling their non-mining activities" (Stilwell, 2004: 7). The unbundling of non-mining activities in this context refers to the separation of actual mining activities from activities, such as the manufacturing of products, that utilise mined minerals, such as platinum, but are not part of the direct mining activities (non-core or non-mining activities) (Robinson, 2016: 2).

The engineering expertise in the South African mining industry is unmatched, according to Stilwell (2004: 7). He therefore states that the current focus of the mining industry should remain where it is in order to meet the technical challenges that lie ahead. Stilwell (2004: 7) further emphasises that other forums (horizontal/side-stream industries) outside the mining industry should address the matter of adding value to South Africa's raw minerals. The Industrial Development Corporation (IDC) believes that undertaking greater levels of downstream beneficiation can foster the development of backward, forward and horizontal industrial linkages, thereby creating employment and facilitating skills development and technological innovation, which will boost industrial growth (Soko and Balchin, 2012: 9).

Backward and upstream linkages are created by large local markets. These are the goods and service inputs used at each stage of the value chain (Malango, 2015: 3). A large local market supports locally produced intermediate goods, giving a comparative advantage to those goods, subject to the economies of scale in their production, while lowering costs for downstream producers. Therefore, upstream linkages can be defined as the distribution chain that connects a producer or supplier with customers; and backward linkages are channels through which information, material and money flow between a company and its suppliers and create a network of economic interdependence; it is the "main channel of technology transfer from the commodities sector to the broader economy" (Teka, 2011: 8). Upstream beneficiation refers to raw minerals, such as platinum in its unprocessed form, being transformed into valuable (value-added) products mostly in other countries, which is currently the case with platinum produced in South Africa (Malango, 2015: 3). A sector that has received little attention, specifically within the South Africa context, is horizontal or side-stream linkages and related industries critical for the operation and competitiveness of the minerals industry (Malango, 2015: 3). Mining creates the "critical mass" necessary for the establishment of these industries (Esterhuizen, 2013: 1).

It is, however, important to bear in mind that the local PGM sector is greatly affected by the global economy due to global integration and a focus on exports (merSETA, 2013: 25). It was noted by the Chamber of Mines's senior executive Roger Baxter, that the value and amount of downstream beneficiation already occurring in South Africa is significantly underestimated (Esterhuizen, 2013: 1).

Mining companies should actively support side-stream and downstream processes, support material funding arrangements, provide inputs into the domestic fabricators at world-determined prices, support training and support market development (Baxter, 2013: 4; 22). The Chamber of Mines states that a growing downstream mineral beneficiation sector is only possible if a facilitating investment environment is created that attracts global manufacturing companies to invest or expand in South Africa (Baxter, 2013: 42).

South Africa’s mining sector makes excessive use of the domestic economy and supplies to many associated industries that use mining products to keep the wheels of the South African economy moving (IMA, 2013: 1). According to the International Mineralogical Association, around 90% of the country’s steel is fabricated locally from locally produced minerals. “In 2009, the Chamber of Mines estimated that around R200-billion in value was added to the local economy through the intermediate and final product industries that use minerals produced by South Africa's mines” (IMA, 2013: 1). This may indicate that we can contribute exponentially to the economy through the improved local use of minerals such as platinum.

The IPAP argues that the introduction or expansion of beneficiation into all sectors of the South African mining industry might be established through collaboration and cooperation between government and industry, and between firms. However, universities should also play a role in these collaborations, as emphasised by the triple-helix model. The document further states that “government policy seeks to ensure a restructuring of the economy to set it on a more value-adding, labour-intensive and environmentally sustainable growth path” (IPAP, 2013: 2).

5.3.2 The stages of platinum beneficiation

Before attempting to study the beneficiation or manufacturing of any platinum product, a good understanding of the platinum beneficiation value chain is critical. However, to understand this, one firstly needs a general understanding of what a value chain is. Arline (2015: 1) defines a value chain as “the full range of activities – including design, production, marketing and distribution – businesses go through to bring a product or service from conception to delivery”. For companies producing platinum products “the value chain starts with the raw materials used to make their products, and consists of everything that is added to it before it is sold to consumers” (Arline, 2015: 1; IDC, 2013: 22).

Platinum group metals are recovered through underground and open-pit mining from polymetallic sulphide ores containing PGMs. Platinum beneficiation typically goes through five stages, namely mining; crushing and milling (concentration); smelting; refining; and fabrication (Ndlovu, n.d.: 2). Stage one (primary stage) is the mining of various metals such as platinum ore or concentrate, and includes activities such as drilling, cutting, hauling, hoisting, etc. (Lundall et al., 2008: 88; Ribeiro, 2009: 23; IDC, 2013: 22; Ndlovu, n.d.: 2). Stage two (crushing and milling stage) is the processing stage where concentrate is converted into bulk intermediate products such as composite concentrates (Ribeiro 2009: 23; Lundall et al., 2008: 7; Ndlovu, n.d.: 2).

Stage three is the smelting stage (mixed low grade, solid matte converting), which is the first stage where PGM concentrate can be sold, but with limited options. Stage four is the refining stage where foundries convert the intermediate products into castings or semi-processed products (Lundall et al., 2008: 7; 88; IDC, 2013: 22; Ndlovu, n.d.: 2). This stage is also referred to as “engineering or machine shops”, which are responsible for manufacturing products, parts, components, tools, forgings and moulds as well as the fabrication of products and structures (Lundall et al., 2008: 7). At this stage, the degree of value-add increases substantially due to the use of additional resources and inputs such as skills and technology (Lundall et al., 2008: 7; IDC, 2013: 22). The last stage (fabrication stage) is where the processed platinum is transformed into finished products and incorporated into various end applications such as catalysts and fuel cells for direct sale (Lundall et al., 2008: 7; Ribeiro, 2009: 23; Ndlovu, n.d.: 2). Activities at this stage include rolling, moulding, machining and assembling (Lundall et al., 2008: 7), and employment opportunities are significantly larger than those presented by the first four stages (Lundall et al., 2008: 7). On the chemical side, this includes catalysts used in fuel cells (IDC, 2013: 22). Although the Chamber of Mines believes that the manufacturing sector in South Africa is rather well equipped to carry out downstream value-added processing of semi-processed minerals, Lundall et al. (2008: 7), there is also the belief that the level of beneficiation of platinum metals, among others, up to stage four is rather low and that there is therefore great potential for growing downstream platinum beneficiation in the country (Soko and Balchin, 2012: 9; Lundall et al., 2008: 90).

5.4 The fuel cell industry in South Africa

Due to the world’s diminishing stock of fossil fuels and the negative effect it has in terms of climate change, as is evident through the global warming crisis, South Africa, as in the case of other countries, will face challenges with its current energy system in future. It is predicted that the demand for energy will increase by more than 25% by 2025 due to the rising world population. There is therefore increasing pressure to find alternative energy sources (HySA PADEP, 2015: 3; IDC, 2013: 14). Alternatives or renewable sources of energy to reduce the carbon emissions polluting the environment are needed. This need has led to the adoption of a global hydrogen economy, as coined by John Bockris in 1970 (HySA PADEP, 2015: 5). In short, the hydrogen economy emphasises that hydrogen gas is the universal carrier of energy and links all sources of energy production with all points of energy consumption (HySA PADEP, 2015: 5).

Hydrogen and fuel cell technologies are regarded as a 21st century energy solution – an attractive sustainable environmental alternative to fossil fuels to address the energy issue as well as climate change worldwide (HySA PADEP, 2015: 25; Jansen, 2016: 11). South Africa has realised the potential of this technology and is therefore looking into the technology in an effort to develop clean and reliable alternative energy sources to fossil fuels in the country. Therefore, the country is driving the research and development activities of hydrogen fuel cell technology (HFCT) as the PGMs used in the technology can provide the country with possible socio-economic benefits; as the human capital development required for this sector could lead to job creation; and as this technology is a viable alternative renewable-energy source essential to reducing CO_2 and greenhouse gas emissions emissions so that the country can meet its global Green Economy targets (HySA PADEP, 2015: 11). However, South Africa has entered the fuel cell field rather late, with other areas such as Japan, the European Union and the U.S. being at the forefront of the technology. South Africa therefore needs strong triple-helix collaborations which may ensure technological catch-up and global competitiveness in the fuel cell industry, as previously stated.

5.4.1 Green Economy

The Green Economy has been identified as a significant growth area as a result of the rapid expansion of the green manufacturing industry in South Africa (merSETA SSP, 2016: 55). Therefore, in the South African context, the Green Economy relates to growing economic activity in the green industry sector and an economic shift towards cleaner industries and sectors with a low environmental impact compared to its socio-economic impact (Green Economy Accord, 2011: 7). As South Africa recognises the opportunities that may be presented by developing industries able to combat the negative effects of climate change, it encourages the development of such industries, which typically includes fuel cells (NDP, 2013: 123). The country seeks to implement nationally appropriate mitigation actions to ensure a reduction of emissions by 34% by 2020 and by 42% by 2025. A further target for South Africa is to reduce its reliance on coal mines for 80% of its energy, which requires new ways to generate clean energy for sustainable economic and social development (Department of Environmental Affairs, 2007: 1). South Africa’s long-term mitigation scenarios enabled the development of a national climate policy based on what is required by science to limit temperature increase to 2 ^{o}C above pre-industrial levels (Department of Environmental Affairs, 2007: 1).

5.4.2 Market for fuel cells

Currently, petrol and diesel catalysts still represent the largest market demand for PGMs; however, platinum-based catalysts in fuel cells represent the next major growth opportunity for South Africa’s platinum resource base (IDC, 2013: 3). The market for fuel cell technology in South Africa is rather small as there is limited demand. However, countries globally are preparing their industries for a change-over to fuel cell technology, such as Japan, who has moved from primarily focusing on nuclear power to a hydrogen and fuel cell focus after the Fukushima-Daiichi Nuclear Power Plant disaster in 2011 (Hydrogen London 2014: 8, Maeda, 2003: 3). The change-over will dramatically increase the market for fuel cells, and South Africa could be a supplier to these global industries, provided it establishes a globally competitive fuel cell industry. Throughout history initially expensive new technologies and interventions became more affordable as markets matured, and advanced research and development (R&D) resulted in increased efficiencies and productivity (HySA PADEP, 2015: 5). This may be the case for fuel cell technology in South Africa as the cost of fuel cell systems in the country is currently extremely high due to the small scale of manufacturing (Jones and Botha, 2014: 317). It is hoped that, as demand for the technology grows, industry will grow and bring about a price reduction. Cost reduction for this technology can also typically occur through improvements in design, using different materials and improving production technology (Jones and Botha, 2014: 317).

As discussed in detail below, HySA has R&D activities specifically focusing on these issues, seeking to address elements of fuel cell innovation that will likely provide valuable opportunities for global industry participation (Jones and Botha, 2014: 318). However, fuel cell innovation can only be achieved through developing the necessary knowledge, skills and infrastructure, which is dependent on continued funding, research into the commercialisation opportunities and the creation of a viable local industry by encouraging local deployment in key applications (Jones and Botha, 2014: 318).

As the manufacturing of platinum group metals in catalytic converters has been undertaken in South Africa since the 1990s, it is not a new concept for the country and may indicate that South Africa would be able to take this industry to new heights. In catalytic converters platinum is used to oxidise carbon monoxide and hydrocarbons. Platinum is particularly effective under oxygen-excessive conditions and is therefore often the metal of choice for diesel and petrol applications (Golunski, 2007: 162). Dewar (2012: 900) believes that, due to the catalytic converter industry's already installed capacity for coating PGMs, it may be a natural facilitator for the development of technologies for the production of fuel cells going forward. The catalytic converter industry in South Africa already has among the highest local content and the highest local value addition of any automotive component category, and has a well-developed value chain that could aid the development of an infrastructure for fuel cell industry in the country (Dewar, 2012: 900).

Various stakeholders, including the Chamber of Mines, believe that South Africa does indeed have the potential to position itself as a global leading manufacturer, producing fuel cells and alternative clean power (Soko and Balchin, 2012: 9). However, for this initiative to succeed, South African policymakers need to be willing and able to address the barriers in developing the necessary capacity to enable downstream beneficiation (Soko and Balchin, 2012: 9). Perrot (2013: 1) also contributes to this, stating that "South African policymakers need to provide extensive policy support and subsidies to hydrogen fuel cell investors and manufacturers, and should nurture technology-specific programmes that will help to bring locally produced or even licensed fuel cell technologies to market". As markets for fuel cells will need to be expanded, policies that support small, local entrepreneurial firms across the fuel cell supply chain could also be extremely beneficial (Perrot, 2013: 1).

5.4.3 Advantages and challenges of fuel cell development in South Africa

The development of a fuel cell industry in South Africa could lead to substantial job creation in knowledge-based industries, with estimates potentially in excess of 500 000 by 2040 (Jones and Botha, 2014: 318). It could attract international fuel cell technology players as well as substantial foreign direct investment (Jones and Botha, 2014: 318). As the fuel cell industry is at an experimental stage, most of the present employment opportunities are limited to highly skilled R&D staff located at universities and innovative small and medium enterprises (SMEs) (IDC, 2013: 20). Job categories currently associated with the fuel cell industry typically include chemists; mechanical, chemical, industrial and electrical engineers; materials scientists; laboratory technicians; factory workers; machinists; power plant operators and maintenance staff; bus, truck and other fleet drivers; vehicle technicians; fuelling infrastructure installers; and hydrogen production technicians (IDC, 2013: 20). Although current job opportunities in the field are predominantly specialist-based, it is believed that, as the technology moves into the early phases of commercialisation, job opportunities may arise in manufacturing and sales as well as in the deployment stage, which according to Jones and Botha (2014: 321) will provide most job opportunities.

The country already has numerous advantages that may aid the development of such an industry. These include that there is a political commitment to address beneficiation as well as energy provision and security challenges; that the country has experience in the demonstration and deployment of fuel cells in a range of applications; that it has experience in the testing and development of fuelling technologies; that it has an expanded manufacturing base supported by government initiatives; that it has access to African markets; that it has access to technical and engineering knowledge and skills in relevant sectors; and finally that the country has businesses that could adapt their services to the fuel cell sector (Jones and Botha, 2014: 318).

5.4.4 The need for a triple-helix partnership

For a fuel cell industry to emerge and stabilise it requires technology and product development in the form of manufacturing at the scale needed to reduce cost; investment in R&D activities to reduce material costs and improve performance; and market development and regulation (Jones and Botha, 2014: 319). In South Africa visible coordination between government departments in determining priority levels, setting strategic objective and formulating implementation plans for fuel cells is lacking and there seems to be no long-term certainty and regulatory incentives to stimulate the market (Jones and Botha, 2014: 319). Therefore, to accelerate the development of this industry and ensure its success there are various preconditions that need to be present. These typically include that government needs to be committed to long-term investment in the sector; that the long-term vision should be endorsed by industry stakeholders and government; that government should appoint a "champion" able to drive action; that adequate governance structures should be in place to ensure alignment of actions across government, industry and universities, which is indicative of the importance of triple-helix dynamics; and that further detailed work on fuel cell prospects should be commissioned, with a focus on future economic, competitiveness and employment impacts that inform the decision whether or not to endorse fuel cells (Jones and Botha, 2014: 322).

Further emphasising the necessity of triple-helix dynamics for the possible successful development of a South African fuel cell industry is Jones and Botha's (2014: 323) emphasis on various interventions needed by government, industry and universities. Government should ensure fiscal incentives to underwrite early market adoption, undertake public procurement of fuel cells to create demand, provide market intelligence, develop standards and product certification, and develop grid connection policy. Industry should invest in advanced procurement programmes, define target specifications, showcase new solutions, sponsor local enterprises to provide product support, and support the training and upskilling of work forces. Universities should ensure collaborative research with international suppliers, create clusters of interest and expertise, and commercially exploit the outcomes of research and development activities (Jones and Botha, 2014: 323).

5.5 Current state of fuel cell technology applications in South Africa

Although the fuel cell industry is still rather small in South Africa, there has been significant progress in using this technology in various applications, specifically in the form of field trials. Mazibuko (n.d.: 3), emphasises that it is inevitable for key players to work together, citing the triple-helix approach. The following section, although not providing an exhaustive list, highlights key developments in fuel cell application in South Africa. Although the below examples have not all yet reached a complete triple-helix "balanced" form, most are emergent partnerships that could be strengthened by triple-helix collaborations.

5.5.1 Community housing electricity

Fuel cell mini-grid technology is an economically competitive alternative to extending grid transmission lines for rural communities far away from the existing grid (Turok, 2015: 1). It provides an opportunity to electrify rural communities at a faster pace than through extending the grid, and is more cost-effective than diesel generators (Turok, 2015:1). In August 2014, Amplats (industry) and fuel cell manufacturer Ballard Power Systems (industry) launched the worlds' first methanol-based fuel cell mini-grid system as a 12-month field trial in collaboration with the South African power utility Eskom (industry) and the Department of Energy of South Africa (government) at the Naledi Trust community (Ballard, 2014: 1; Anglo American, 2015: 6). The Naledi Trust community was identified as suitable, due to it not having access to grid power (Turok, 2015: 1; Ballard, 2014: 1). The fuel cell system set up for the community continues to power up 34 households (Turok, 2015: 1).

5.5.2 Chamber of Mines

The 100 kW fuel cell installed in December 2014 at the Chamber of Mines in Johannesburg was the culmination of a four-year initiative to demonstrate the applicability of fuel cell technology in South Africa (Chamber of Mines, 2017: 1). The fuel cell produces around 70% of the organisation's electricity and produces enough power to meet the needs of around 100 average South African households (Chamber of Mines, 2017: 1; IDC, 2015: v1). The project was a collaboration among the IDC (industry), the Chamber of Mines (government) and Mitochondria Energy (industry) to fund the research and development of the fuel cell (IDC, 2015: 1).

5.5.3 Underground mining

Fuel cells are attracting increased attention as an alternative for underground technology in mining environments. Diesel vehicles are more mobile and productive, but compliance with emissions regulations reduces their actual productivity. Implats fuel cell coordinator Fahmida Smith highlights that diesel-fuelled load haul dumpers used in underground mines release diesel particulate matter that is a chemical with an exhaust temperature of about 350 °C (Nosarka, 2016: 1; Jansen, 2016: 58). Battery-powered vehicles on the other hand have zero emissions underground and good mobility, but suffer lower productivity due to low onboard energy storage and long recharging time (Miller et al., 2012: 533). A fuel-cell-driven load haul dumper has zero diesel particulate matter, does not emit any carbon monoxide, emits 40% less carbon dioxide and produces negligible sulphur oxide and nitrogen oxide (Nosarka, 2016:1). Fuel-cell-powered vehicles are also cost-competitive, as lower recurring costs and reduced ventilation costs lead to higher vehicle productivity (Miller et al., 2012: 534; Nosarka, 2016: 1). Fuel cell technology therefore presents an alternative as it incorporates the advantages of the other technologies while avoiding their disadvantages; these fuel-cell-powered vehicles have the mobility, power and safety of a diesel unit, combined with the environmental cleanliness of a battery vehicle underground (Miller et al., 2012: 533). Due to these environmental benefits, fuel cells have been labelled as a "sustainable technology" to justify their implementation in mines (Jansen, 2016: 11).

5.5.4 Impala Platinum forklift

Implats has launched a prototype fuel cell forklift and hydrogen refuelling station at its refineries, which have been operating in the nickel dispatch area of Implats's base-metal refinery in Springs since October 2015 (Creamer, 2016: 1). This project was a collaboration between Implats (industry), University of Western Cape (UWC) (university), HySA Systems (university), and the Department of Science and Technology (DST) (government), clearly emphasising its triple-helix nature. In a forklift the fuel cell supplies the base load power for normal driving, which is combined with a battery allowing for operation at peak power loading (Impala Platinum, 2016: 3). This typically occurs during lifting and inclined acceleration (Impala Platinum, 2016: 3). Hydrogen is stored at low pressures by onboard metal hydride containers that feed the fuel tank with hydrogen (similar to petrol and diesel) (Impala Platinum, 2016: 3). The forklift is used at the dispatch area in the base-metals refinery and does not produce any fumes or noise compared to its diesel counterparts. This system creates demand for the country's metals, as the fuel cells require platinum and the hydride uses nickel; it is therefore also aligned to the country's "green" technologies strategy (Impala Platinum, 2016: 3).

There are collaborative efforts by numerous departments of the South African government with links to strategic local and international partnerships through the Implats roadmap. This roadmap aims to develop fuel cell technology to drive knowledge-based skills development and job creation, and to increase foreign direct investment in South Africa (Impala Platinum, 2017: 3). Opportunities identified through local manufacturing are entrenched in the roadmap through extensive collaboration between industry, government and universities in South Africa, which clearly indicates the awareness of the importance of triple-helix collaborations (Impala Platinum, 2017: 3).

5.5.5 Hydrogen South Africa (HySA)

The DST realised that HFCT could be used as an initial science and technology platform to facilitate innovation and knowledge generation (key to the triple-helix model) to utilise South Africa's natural resources (HySA PADEP, 2017: 1; HySA Systems, 2014: 1). Therefore, to support the DST's mandate to ensure the mastering of technological change in South Africa's economic and social context, the HySA flagship programme was initiated, approved by the cabinet in May 2007 and officially launched in September 2008 (HySA Systems, 2014: 1; HySA PADEP, 2017: 1; Mining Weekly, 2012: 1; RSA, 2015: 1).

The aim of the 15-year HySA National Flagship Programme is primarily to develop South Africa's intellectual property, knowledge base, human capital, products, components and processes to facilitate participation in the global HFCT arena (HySA Systems, 2014: 1). It furthermore strives to transform South Africa from a resource-based economy into a knowledge-based and driven economy, with innovation (enabled through triple-helix dynamics) playing an important role in enabling high-value addition to South Africa's mineral wealth (HySA Systems, 2014: 1; RSA, 2015: 1; HySA Catalysis, 2017: 1). The programme has been implemented in the context of the DST's various innovation strategies, such as the minerals beneficiation strategy of the Department of Mineral Resources (DMR), the Integrated Resource Plan of the Department of Energy and the industrial development strategies of the Department of Trade and Industry (dti) (HySA Systems, 2014: 1).

The project needed to focus on building the required infrastructure and required the expertise of overseas specialists familiar with the research gaps that needed to be addressed (Campbell, 2017: 1; Mining Weekly, 2012: 1). Through the project the country has successfully trained its own researchers and are making an impact in the sector globally (Campbell, 2017: 1). The 2016/2017 budget for HySA was around R81million, which was divided into project funding of a little less than R64 million and human-resources funding of R17,5 million (Campbell, 2017: 1). The main countries actively engaged in hydrogen fuel cell research include Australia, Austria, Brazil, Canada, China, France, Germany, Iceland, India, Italy, Japan, the Republic of (South) Korea, the Netherlands, Norway, the Russian Federation, South Africa, the United Kingdom and the United States (U.S.), all being part of the International Partnership for Hydrogen and Fuel Cells in the Economy (Campbell, 2017: 1).

The main aim of the project is to make South Africa one of the most important sources of catalysts in the world, with a market share of 25% by 2020 (Campbell, 2017: 1; HySA Systems, 2014: 1; RSA, 2015: 1). Additional objectives include developing value-added manufacturing in the country by setting up a platinum catalysis value chain; creating a domestic cost-competitive hydrogen generation infrastructure based on renewable resources; stimulating demand for PGMs, platinum in particular; and ensuring that the development of a local hydrogen energy industry is done on an inclusive and equitable basis (Campbell, 2017: 1). The achievement of these objectives should ensure the local beneficiation of platinum, the commercialisation of South African intellectual property, the establishment of a domestic fuel cell manufacturing sector and the creation of potential to explore the use of fuel cell technology in niche markets, thereby creating jobs (Campbell, 2017: 1; HySA Systems, 2014: 1).

To address technological challenges facing the development and deployment of commercially viable hydrogen fuel cells in the country, three centres of competence (CoCs) were established to focus on the three main areas necessary to achieve the technological goals of the programme (Campbell, 2017: 1). These CoCs include HySA Catalysis, co-hosted by the University of Cape Town (UCT) and minerals beneficiation science council Mintek; HySA Infrastructure, co-hosted by the Council for Scientific and Industrial Research (CSIR) and the North West University (NWU); and HySA Systems, hosted by the UWC (Campbell, 2017: 1).

The HySA programme has facilitated the successful graduation of around 59 Doctor of Philosphy (PhD) and master's students in both engineering and scientific disciplines involved in HySA research, and most of them are now employed by the HySA programme. Currently, the CoCs employ more than 50 PhD and master's graduates, both scientists and engineers. The CoCs have produced more than 151 peer-reviewed publications, registered nine patents and deployed seven technology prototypes, and there are five technology demonstrations taking place to validate the technologies and the performance of the systems (Campbell, 2017: 1). Each HySA CoC forms part of a national network of research "hubs" and "spokes" through collaboration with institutions and partners from the R&D sector, higher education, as well as industry, emphasising triple-helix relationships in order to achieve the HySA strategic objectives (HySA Systems, 2014: 1).

5.5.5.1 HySA Catalysis centre of competence

HySA Catalysis focuses on the development of platinum-based catalysts and has developed a spin-off company called HyPlat, which has been commercialised and is selling some of its products for both commercial and R&D use (Campbell, 2017: 1; HySA Catalysis, 2017: 1). The products developed by HyPlat have been subject to successful international tests and it is recognised internationally as one of the emerging players in the fuel cell sector (Campbell, 2017: 1; HySA Catalysis, 2017: 1). This CoC has partnered with various additional institutions, including FlyH2 Aerospace, UWC, University of KwaZulu-Natal, NWU, Nelson Mandela Metropolitan University, the CSIR, Greenlight Innovation, Hot Platinum, the Paul Scherrer Institute, Powertech and the Western Cape Tooling Initiative (HySA Catalysis, 2017: 1).

The commercial and academic goals of HySA Catalysis is to establish South Africa as a major global exporter of catalysts and fuel cell components, to develop a fuel cell supply chain in South Africa with local manufacturing partners, academically to become internationally recognised as a fuel cell and hydrogen research institute, and to develop human capital for a knowledge pool of South African engineers and scientists for the fuel cell industry (HySA Catalysis, 2017: 1).

5.5.5.2 HySA Infrastructure centre of competence

HySA Infrastructure focuses on hydrogen production storage, distribution, safety, codes and standards (Campbell, 2017: 1). This CoC is pioneering the production and use of renewable hydrogen in South Africa for fuel cell and energy storage applications in view of the globally increasing focus on renewable energy (HySA Infrastructure, 2016: 3; Langmi and Bessarabov, 2013: 10; HySA Infrastructure, 2017: 1). This may lead to the development, advanced manufacturing and application of new products as well as hydrogen storage materials and processes that improve the competitiveness of the South African energy sector (HySA Infrastructure, 2016: 1; 3).

The strategy emphasises developing human capital, roadmaps and a technology development matrix for hydrogen fuel cell components and systems, promoting local and international collaborations, ensuring conformity, and understanding market needs in renewable hydrogen production and storage (HySA Infrastructure, 2017: 1). The technical objectives relate to the development of hydrogen generation systems and prototypes linked to renewable energy sources as well as hydrogen storage and distribution technologies, which typically includes proton exchange membrane (PEM) electrolysers and electrolyser systems linked to renewable-energy, hydrogen storage, hydrogen reticulation and delivery, systems integration, PGM recycling as well as involvement in the public awareness project (HySA Infrastructure, 2017: 1).

The long-term vision of HySA Infrastructure is to be recognised as a leader in selected applications and to be a well-established internationally recognised CoC for research and product development in aspects such as hydrogen production, storage and distribution. It aims to contribute to the South African fuel cell industry's global competitiveness, while also addressing the economic and social needs of the country (HySA Infrastructure, 2017: 1).

Some of the services HySA Infrastructure performs include fuel cell testing for telecommunication, mobility and stationary-power applications; consultation on fuel-cell-powered vehicle development and conversions in collaboration with the NWU's mobility research group famous for its award-winning solar-powered car; and consultation on membrane electrode assembly (MEA) development for automotive fuel cell applications (HySA Infrastructure, 2016: 2). HySA Infrastructure has selected the following future projects: a power-to-gas research platform for South Africa, which includes methanation processes; fuel cell vehicles and duel fuel hydrogen applications; and closed-cycle combined heat and power 3 kW (electric), 15 kW (thermal) duel-fuel micro gas turbine to prove that hydrogen produced from renewable sources can be mixed with natural gas to increase efficiency and reduce carbon dioxide emissions of South

Africa's gas turbines (HySA Infrastructure, 2016: 2). The CoC is currently looking at spin-off applications for the technologies it is developing (Campbell, 2017: 1).

5.5.5.3 HySA Systems centre of competence

HySA Systems focuses on pulling together the work of the other two CoCs to create and validate complete systems (Campbell, 2017: 1; Mining Weekly, 2012: 1; HySA Systems, 2014: 1). This CoC is oriented towards industry, technology and prototype development and has demonstrated on many occasions its ability to develop, build, commission and validate energy systems (HySA Systems, 2014: 1). It is also responsible for the development, testing, validating and commissioning of key technologies, including MEAs for high temperature PEM fuel cells, high-temperature PEM fuel cell stacks, metal hydrides for hydrogen storage and compression, lithium-ion batteries and system integration of energy storage devices for domestic and automotive applications (HySA Systems, 2014: 1).

Some of the main objectives are to develop HFCT systems and prototypes, to perform technology validation and system integration and to focus on system-oriented material R&D in three key HySA programmes, (1) namely combined heat and power (CHP), (2) portable systems and (3) hydrogen-fuelled vehicles (HySA Systems, 2014: 1). This CoC is currently working hand in hand with Implats on implementing a full-scale technology demonstrator forklift, as mentioned earlier. The project is so successful that Implats is keen to expand the number of fuel cell forklifts in its service (Campbell, 2017: 1). Additionally, related to the HySA initiative is the establishment of the Hydrogen South Africa Public Awareness, Demonstration and Education Platform (HySA PADEP) under the National Research Foundation through the South African Agency for Science and Technology Advancement (Mashau, 2015: 5). As the adoption of any new technology requires public awareness, this platform was established to ensure the fuel cell technology is marketed on a local and global scale, creating awareness, visibility and acceptance among the public, industries, entrepreneurs and key decisionmakers in South Africa on various aspects of using HFCT in the alternative energy industry (HySA PADEP, 2017: 1). In addition, four fuel cells have been installed in four science centres around the country to support and engage the public to create an understanding of the benefits of using this technology for South Africa (HySA PADEP, 2015: 26).

5.6 Summary

The aim of this chapter was to provide an overview of the current fuel cell industry in South Africa. Although the industry is rather small with limited demand, it is steadily gaining interest, especially due to its environmental benefits. There are various emergent partnerships in the area of fuel cell technology in South Africa, but most of these tend to be between industry and government entities. Moving towards a triple-helix model by also actively engaging with universities could strengthen these partnerships. However, South Africa does have a leading example of a triple-helix collaboration in the fuel cell space called HySA. This programme is a partnership between various universities, industry players as well as the DST, all working together to further the fuel cell industry. Therefore, the basic footwork for a fuel cell industry in South Africa based on triple-helix collaborations already exists and it should be possible to further develop this industry.

SECTION C: FIELD EVIDENCE

CHAPTER 6: EVIDENCE FROM SITE STUDIES

The purpose of this chapter is to present the evidence collected through fieldwork. The chapter consists of two sections. The first section is an overview of the participants who took part in the study, indicating their respective organisations/companies, the institutional spheres they represent, their job titles and how long they have been in the fuel cell industry. In the second section, the findings are presented in terms of major themes identified in Chapter 5. The focus of this thesis was to look at the current state of the fuel cell industry globally and in South Africa, whether there are forms of triple-helix dynamics already taking place in the South African fuel cell context and whether key players in the industry see the triple-helix model as a possible facilitator of further development of the fuel cell industry in the country. The HySA centres of competence (CoCs), based at three respective universities, were established though a Department of Science and Technology (DST) Hydrogen South Africa (HySA) flagship programme. This initiative is not only the main driver for the development of a local fuel cell industry, but through the CoCs there are collaborations with industry and other government departments. This indicates the possibility that, in the fuel cell context, some form of triple-helix dynamics, typically on a continuum from high to low, is already taking place through these CoCs. It is against this background that these three CoCs were selected to do site studies for this thesis.

As the main focus of this thesis is three small site studies, each representing a HySA CoC, it was crucial to ensure that the respondents representing these CoCs were senior experts in the fuel cell field. Over and above these respondents, key entities from industry and government who have partnerships with these CoCs also formed part of the sample. The reason for this was to ensure that all spheres of the triple-helix (university, government and industry) partnership were represented, but taking care that the study was still based and structured around the CoCs, which formed the main focus. To guarantee that only the most relevant participants were selected, purposive sampling was used (explained in more detail in Chapter 1), and the sample size for this study therefore came to 11. The characteristics of the participants and the organisations they represent are illustrated in the table below (indicating the triple-helix spheres). However, it should be emphasised that, although the participants took part as representatives of their organisations, the information provided remains the views of the individual participants and cannot be taken to necessarily represent the view of their organisations/companies as a whole. Also to be noted is that, although the participants will be referred to by the participant name allocated to each of them in Table 3 to ensure anonymity, their organisations' names are mentioned in some cases.

Table 3: Interviewed organisations by triple-helix sphere

Participant	Participant organisation	Sphere represented	Job title	Experience in the fuel cell field
Participant A	DST	Government	Director: Hydrogen and Energy	In this industry since 2006.
Participant B	dti	Government	Deputy Manager	In this industry since 2006.
Participant C	Implats	Industry	Fuel cell coordinator	In this industry since 2005.
Participant D	Amplats	Industry	Principal Market Development	In this industry for four years.
Participant E	IDC	Industry	Senior project development manager	In this environment for 20 years, of which six has been focusing on industry development).
Participant F	IDC	Industry	Chemical engineer in the Industrial Infrastructure Unit	Involved in the areas of energy.
Participant G	HyPlat	Industry	Operations Manager	With HyPlat for three years.
Participant H	CSIR	Science council	Research Group Leader of the research group Clean Energy Technologies	In the industry for 34 years.
Participant I	CSIR	Science Council	Key Programme Manager	With the CSIR for five years, with hydrogen storage background.
Participant J	HySA Catalysis	University	Product Development Manager	With university for nine years.
Participant K	HySA Infrastructure	University	Programme Manager for Renewable Hydrogen	With HySA Infrastructure since 2013; started PhD degree on fuel cells in 2010.
Participant L	HySA Systems	University	Chief Director	In this industry since 2008; was directly involved in establishing the HySA CoCs during 10-year term with DST.

The selected participants were interviewed through a semi-structured interview guide to ensure only the most relevant information related to the thesis was collected and to allow the participants the freedom to provide any additional information they deemed essential. The overall aim was to stablish the potential of triple-helix dynamics to allow for the development of a local, globally competitive fuel cell industry in South Africa. To inform this overall aim, the research questions were focused on uncovering whether triple-helix dynamics are taking place in the South African fuel cell industry; who the current main players in industry, government and universities within the fuel cell context are; whether collaborations between triple-helix spheres have yielded any positive outcomes for the fuel cell industry in South Africa; and what the benefits would be for the economy and employment if we succeed in developing a local fuel cell industry in South Africa.

The findings that emanated from the field work will be discussed according to three identified main themes. It should be noted that these themes are not necessarily mutually exclusive, as each plays an essential part in the development of a fuel cell industry in South Africa. These themes are: (1) platinum beneficiation in South Africa; (2) the fuel cell industry in South Africa; and (3) triple-helix relationships in the fuel cell context. These themes have various categories that relate to the research questions of the study.

6.1 Platinum beneficiation in South Africa

South Africa mainly exports its raw platinum for final product manufacturing overseas and then imports these products back into the country at higher prices, therefore not utilising its natural resources to its full potential. The study accordingly argues for the increased utilisation of platinum resources for local beneficiation and fuel cell manufacturing to reduce the importation of platinum products and increase the exportation of value-added platinum products. Benefits from this may include the growth of a strong manufacturing sector, while the development of a fuel cell industry that utilises platinum could increase local platinum demand, which in turn has its own economic benefits such as job creation. The views of key players in the industry are vital to establish whether the notion of increased platinum beneficiation in general in South Africa is feasible and to gain an understanding of what is required to develop a fuel cell industry in the country.

6.1.1 Viability and benefits of platinum beneficiation in South Africa

It is firstly necessary to understand what the views are around the viability of platinum beneficiation in South Africa to get some idea of whether platinum beneficiation may act as an incentive for the development of a local fuel cell industry. In the findings respondents generally indicated that they do believe that South Africa has the potential to increase local platinum beneficiation – some more strongly than others. It was cautioned by five respondents that, although increased platinum beneficiation is viable, it needs to be considered on a case-by-case basis, taking into account various perspectives and reflecting on where the best investments would be made in the long-term. One of the concerns raised was that it cannot be assumed that South Africa has the potential to increase its platinum beneficiation activities because it has large reserves of platinum resources. However, not all respondents held this view equally strongly, with four indicating that they believe that the country’s large amounts of platinum reserves serve as a catalyst for increased local platinum beneficiation. This is supported by the literature emphasising that South Africa’s natural monopoly on platinum favours increased mineral beneficiation (Soko and Balchin, 2012: 9; Erasmus, 2013; Manda and Crosby, 2016: 1).

> Participant A (government): "There is room for increased platinum usage … and we believe that fuel cell technology provides a very real platform for the country to do more of the platinum beneficiation locally."

> Participant L (university): "The whole idea of HySA is to add more value to our platinum resources … I think we are, but we can utilise the opportunity even better if there's a special price for local value chain addition ... we have the mineral, but we don't control the price."

The findings indicate that skills development, capacity development, knowledge building, increased manufacturing, job creation, localisation and the creation of new industries are all benefits that may come from increased local platinum beneficiation in South Africa. The findings validate the literature stating that South Africa is mostly exporting its raw platinum to be transformed into value-added products abroad and then imported back into the country at a high price. This is key, as it is a central argument of the study. The sector is facing rising imports and declining exports of some platinum manufactured products, with the cost of importing final platinum-containing products 14 to 20 times the cost of locally produced products, resulting in a struggling manufacturing sector. The South African beneficiation strategy also emphasises this in stating that South Africa has low levels of mineral beneficiation and most of the country's minerals are exported as ore and semi-processed minerals as opposed to high-value intermediate to finished products (DMR, 2014: 42; DMR, 2011: iii).

Investing in local platinum beneficiation will increase the exportation of value-added products and reduce imports of platinum containing products, which will contribute positively to the South African economy. However, benefits will depend on where the focus is along the value chain, as some elements in the value chain may have greater market potential than others. The importance for creating a stable and sustainable local demand for platinum was emphasised by many, especially in view of the struggling mining industry (and the shrinking platinum industry), which continues to employ thousands of people. The findings indicate that the current mining industry may not be able to create more employment opportunities; it might only be able to retain current jobs. This corroborates the literature stating that, although South African mines used to be able to employ a large workforce, it will be impossible to maintain that same level of labour absorption in the mining industry going forward (Bowman and Isaacs, 2014: 36). However, despite serious challenges facing the South African mining industry, the country is still the world leader in producing platinum group metals (PGMs) (IDC, 2013: 3). It is therefore vital to create new local uses for the platinum produced in the country.

> Participant A (government): "Local platinum beneficiation would lead to us importing less, so by exporting value-added products, we earn more export revenues and if we use the technology at home, we import less and become less reliant on technology coming from outside."

This corroborates the literature stating that South Africa needs to diversify by breaking its dependency on the exportation of its raw resources and by increasing the utilisation of its natural resources through effectively beneficiating locally and increasing exports.

> Participant E (industry): "As the platinum market in South Africa is shrinking, for the mining community it's essential to get new applications for platinum."

> Participant B (government): "It's important to ensure platinum demand is stimulated so to maintain, if not increase jobs, in those sectors; there's knock-on effects we see coming out of the mining industry in terms of the general contribution to the economy."

The findings above regarding the viability of increased platinum beneficiation in South Africa indicate that it is viable, but that there are various elements that need to be considered beforehand. The country is seeking new avenues of utilising its platinum reserves with the shrinking platinum industry and the struggling mining sector, which is a major employer. The local development of new enterprises capable of beneficiating platinum-containing products (such as fuel cells) and exporting them abroad could have multiplying benefits for the country, typically job creation, increased investment and skills development, among others, which would all contribute to the growth of the South African economy.

6.2 The fuel cell industry in South Africa

6.2.1 The state of the industry

Overall, the view is that, although the fuel cell industry is slowly emerging in South Africa, the industry is fragmented. In this context fragmentation refers to the fact that there are various activities taking place in the fuel cell context, but they all occur in isolation. The different entities involved do not share their work so as to further the industry. Although there seems to be a market and although components are being looked at through the HySA initiative, currently there is no commercial manufacturing plant in the country. South Africa is still in the experimental research and development (R&D) stage as far as fuel cell technology is concerned.

> Participant D (industry): "There are about 300 to 400 fuel cell units deployed in South Africa in the telecommunications market … Isando, a local fuel cell company recently announced they are going to set up a membrane electrode assembly producing plant in South Africa."

> Participant L (university): “There are currently no commercial companies in the country, but it is also South Africa ‘s task to stimulate that and we are continuously working on it … HySA Systems are producing fuel cells on a pilot scale ... the centre has established H2Systems, which is negotiating joint ventures with national companies, and we should be able to stimulate the industry, but there is a lot to be done and it is still early days.”

Even though the country does not have a fuel cell manufacturing plant, there are various activities taking place to make this a reality. Companies such as Impala Platinum (Implats) and Anglo American Platinum (Amplats) are actively driving the adoption of fuel cells in South Africa with the support of government (indicating government-industry partnerships). South Africa currently has a number of fuel cell technologies being evaluated and assessed to determine whether they are according to the required standard and to secure a position in the market. The HySA CoCs are developing their own fuel cell technologies, which brings with it competent post-graduate students in the field, commercialisation opportunities and intellectual property rights, all of which contribute to the development of a fuel cell industry. The HySA CoCs are actively engaged in activities such as the manufacturing of fuel cell components and fuel cell demonstrations to increase awareness, which have also given rise to spin-off firms, such as HyPlat, that manufacture MEAs and catalysts (Interview with Participant C: Industry, 2017). At a component level, HySA Systems has high-temperature membrane electrode assemblies (MEAs), which are semi-commercial to an extent as they can produce up to 30 MEAs per hour. It is the only CoC that manufactures complete systems and it has a couple of such systems on the market. It also has a business entity investigating some type of collaborative production with Nedstack, one of the leading proton exchange membrane (PEM) fuel cell manufacturers in the world. Government on the other hand has cautioned that the fuel cell demonstration systems are not performing as they should due to the selection of cheaper technologies that are not compatible with the South African context.

> Participant K (university): “Cheaper, inefficient fuel cell technologies are selected for demonstration projects with the aim of making more profit … there needs to be a shift towards selecting appropriate high-quality technology for demonstration purposes in the country.”

The findings indicate that bilateral negotiations are taking place between various government departments to consider how the uptake of fuel cell technology can be increased, while there are also engagements on this matter across all sectors, including industry, government and universities. Government representatives emphasise that the role of government and other industry players is to support fuel cell spin-off companies to ease the process of navigating innovations and taking the technology to scale.

However, one industry representative is of the view that government should not get involved in industry activities in general, and although they acknowledge the work government has done through the HySA initiative, they emphasise that there is no real business leadership at these CoCs, as they mostly have a technical and scientific focus.

> Participant F (industry): “There needs to be business leadership in these centres and the technical part must be a supporting part.”

> Participant A (government): “We need to continue to make sure the centres of competence are well resourced to continue developing the technology and address the issues of durability and costs of the technology.”

6.2.2 Market growth potential

Findings indicate that the future outlook of the fuel cell industry in South African is rather fragile at the moment. As the country seeks to sell its platinum and deploy fuel cells, it is pushing the technology into the market. In such a “push market” there are currently no market forces to create the environment for a viable fuel cell market. Mining houses were mentioned as the main drivers for fuel cells, as they seek to create new markets for their platinum. However, more than one respondent emphasised that, even though South Africa has platinum, it does not provide the country with an advantage, as the platinum used in these fuel cells is minimal. This finding contradicts the literature stating the wide-scale adoption and commercialisation of fuel cell technologies may result in growth in platinum group metal demand (IDC, 2013: 3).

There are currently insufficient economies of scale in the country to set up a manufacturing plant, and it is therefore crucial to get industry onboard to create the necessary volume. Although there is interest from various stakeholders, industry has not yet fully embraced the fuel cell industry and requires overarching governance support to ensure that industry, government and research institutions work towards the same goal. Until industry is fully onboard, government will need to subsidise and ensure a stable infrastructure and, once industry is onboard, commitment in the form of procurement from government will be needed to manufacture. The findings also indicate that South Africa has a vital role to play within the global fuel cell industry, which is strategically structured to ensure the establishment of joint-venture companies with global partners that are able to complement local initiatives and not necessarily compete to conquer the whole industry.

> Participant L (university): “It would be an advantage to partner with a company that has a global footprint in Europe and China, because China is actually the biggest fuel cell consumer at the moment in the automotive industry.”

It was noted that, to support fuel cell manufacturing, South Africa has been targeting special economic zones for the development of fuel cells, with skills, platinum, cheap labour and government incentives provided in the zones, which indicates that the country does have the potential of becoming competitive in the global fuel cell arena. Currently, the key issues the country is facing with regard to fuel cells is market development and the associated costs, with the majority (seven) of respondents indicating that the cost of fuel cells will come down with market development and adoption. The literature supports these findings as the cost of fuel cell systems in the country is currently extremely high due to the small scale of manufacturing (Jones and Botha, 2014: 317). Two respondents cautioned that the current local fuel cell market will not create economies of scale and that the country should rather import systems and then deploy them locally. This comment contradicts efforts made by various entities to increase applied research in the fuel cell field in an endeavour to establish the country as a global competitor. This indicates that not all players share the same view about the development of such an industry, which limits the potential for increased triple-helix dynamics to develop a local fuel cell industry.

> Participant D (industry): “As you get scale globally, the unit cost will come down and then these fuel cells would be more competitive.”

Respondents had different views on the reason for the high cost of fuel cells with two believing it is caused by the platinum input and six others ascribing it to elements such as the cost of hydrogen transportation for fuel cells among other things. The literature seems to agree that the high fuel cell technology cost is due to all of these aspects and can be reduced through improvements in design, using different materials and improving production technology (Jones and Botha, 2014: 317).

> Participant D (industry): “Fuel cells are not the most cost-effective solution, not because of the platinum – the platinum cost compared to the fuel cell is small – but it has more to do with the unit costs and because there’s not enough scale, you’re producing these fuel cells at a higher cost.”

Respondents argued that South Africa should adopt a global perspective when considering the fuel cell industry, ensuring that there are no trade barriers for technologies produced in the country. As one respondent put it, the fuel cell industry will not survive in the local market itself. The fuel cell market does not have to be local, as long as we manufacture locally for a global market. Industry is looking at global fuel cell players to incorporate the technology into their processes and into the country in order to promote localisation. Six respondents were also of the view that, although the country is able to become a global fuel cell competitor, it needs to consider carefully what market has the greatest potential to tap into. The country should consider whether to focus more on fuel cell applications in the country itself or on being a player in the global fuel cell value chain, becoming a component supplier while leading with technology that puts South Africa at the forefront.

> Participant A (government): “We need to continue putting in the right investments that ensure the technology we develop is not only good for the South African domestic market, as the potential is really in the export market … Our technology has to be robust enough and priced at a point where it’s able to compete at a global scale.”

> Participant H (science council): “We do make sure anything we design or build conforms to national and international norms and standards, so there aren’t any trading barriers with anything produced here.”

When considering the notion of technological catch-up regarding fuel cells, five respondents believe that South Africa started late and is far behind; the country should rather adopt a leapfrog approach (leap frogging is a way to catch up more quickly), as catching-up will not give the country the competitive edge. Although the literature uses the standard term “catch-up”, leapfrogging was emphasised by two respondents as the only way of catching-up with global leaders. The finding that South Africa is far behind supports the literature stating that South Africa has entered the fuel cell field late, with areas such as Japan, the European Union and the United States (U.S.) being at the forefront of the technology. Funding was raised as a key constraint for the development of such an industry; globally the budgets received for fuel cell industries are much greater compared to the South African context.

Related to this is the first phase of HySA initiative, which was called the technology catch-up phase (essentially a leapfrog strategy), where global experts were brought in to direct the CoCs, while students were also sent abroad to acquire additional skills in order to develop the skills pool needed in the country for the fuel cell industry. It was also emphasised that the technology coming through the HySA CoCs is quite competitive globally. However, the issue of time and money needed to develop new technologies was also raised. It was suggested that, rather than spending a lot of time and money on the development of new technologies from scratch (not creating a market), it is better to import a key component and develop it in parallel with other countries to ensure marker creation locally.

> Participant K (university): “The funding we give or get is much lower compared to global companies, and you can’t catch-up unless you have an extremely big budget.”

> Participant J (university): “We were behind, and we weren’t doing any fuel cell research while other countries have been doing it for 20 to 30 years.”

> Participant D (industry): “It is a challenge when research and development take place locally in areas where the global market has already moved on, while we are still catching-up and lagging behind.”

The fuel cell industry, like other technologies, has competing technologies, and findings indicate that batteries are the main competitor of fuel cell technologies for vehicles and stationary power. If the cost of fuel cells is reduced, they will have more benefits than batteries, one of which is that fuel cells provide power for as long as it has fuel, while batteries need to be recharged. Solar was also highlighted as a competitor, especially due to it being much cheaper than fuel cells. However, as the literature indicates, solar has numerous limitations, one of them being that they do not work at night and although solar energy can still be collected during cloudy and rainy days, the efficiency of the solar system drops with fluctuating weather conditions (Understand Solar, 2017:1). Fuel cells are the better alternative to solar power as the technology it is more reliable and efficient.

> Participant L (university): “Solar is much cheaper than fuel cells, the Department of Energy wants fuel cells to be at the same cost price as solar panels, which is tricky … this is a technology that is still an infant industry in the market worldwide, not just in South Africa.”

> Participant H (science council): “Battery electric vehicles are very popular at the moment; they both can find a niche market because batteries work better inside cities, while hydrogen will take you from city to city as batteries won’t last as long.”

This is corroborated by the literature stating that battery electric vehicles are best suited for light-duty vehicles on routes of modest range. Longer distances require a bigger motor, a stronger suspension and better brakes, which add to the weight and which in turn would require bigger batteries. (Samuelsen, 2016: 1). On the contrary, fuel cell electric vehicles can be used to power virtually any size vehicle, making the technology the better alternative. Further in favour of fuel cell technology are carbon tax and environmental obligations. South Africa is moving into the green space and fuel cells are classified as a green technology, which provides us with another advantage when compared with other competing power technologies.

> Participant B (government): "With the coming of the carbon tax, we are hoping it will move people to the green space; once you are only confined to green, then you can say 'let there be competition'."

The application of fuel cells for mining equipment provides a good alternative for the large amounts of diesel used in underground mining, even though extensive investment is required to support the necessary infrastructure. The mining industry is also moving towards automation and fuel cells are well-suited to such an industry.

6.2.3 Policy support for the fuel cell industry

Having the correct policies in place is vital for driving an industry such as the fuel cell industry, but respondents suggested that current policies are not sufficient and are unclear on the role of fuel cells. It is, however, not always possible to pre-empt what policies are necessary for an emerging industry such as the fuel cell industry. Issues raised by the respondents were coordination and misalignment between government departments. It was also noted that the South African Department of Energy talks about renewable energies, but fuel cells are not specifically mentioned to allow for public procurement. Some concerns around HySA commercialisation strategies were highlighted. Additionally, it was argued that a vibrant fuel cell industry needs policies that support equal funding opportunities and encourage a competitive environment.

> Participant D (industry): "The South African government needs to drive policy if you look at what impact fuel cells would have on energy and how that impacts on integrative resource planning … with policy, you can drive the fuel cell industry. If there was a policy for the adoption for fuel cells to provide alternate energy solutions, that would have a positive effect on fuel cell development in the country."

> Participant C (industry): "The dti's IPAP document references fuel cells and their government support for fuel cells, but there is still some misalignment between various government departments …"

On a more positive note the Industrial Policy Action Plan (IPAP) was highlighted as a key policy document in support of fuel cell development for the purpose of platinum beneficiation, although only first appearing in strategy a year ago. The IPAP looks at activities around demonstration, market development as well as technology development. These link to skills development, investment, recruitment and building an infrastructure for manufacturing.

> Participant B (government): "With the IPAP, the focus will sometimes slightly change, but the focus is always around mineral beneficiation … the aim of this policy is job creation, industrialisation, manufacturing and then export development and promotion, and then investment recruitment."

It was emphasised that the mineral beneficiation strategy evaluated all South Africa's mineral resources against opportunities for the country in terms of adding value – and platinum always comes out on top. In contrast, one participant indicated that there are no policies in support of fuel cell technology development in the country and that funding is made available only for R&D purposes. This indicates a clear misalignment between government and industry players in support of the fuel cell industry. Strong triple-helix relationships are required to ensure that communication channels are open to keep all players in this industry abreast of developments in support of fuel cell development.

6.2.4 Benefits of developing a local fuel cell industry in South Africa

Some of the benefits highlighted through the development of a local fuel cell industry include knowledge-based job creation, skills development, mineral beneficiation, deployment into other industries and economic growth. This finding corroborates insights in the literature highlighting that numerous states in the U.S. have realised the potential of fuel cell technology as a high-growth industry to facilitate job creation and increase economic benefits; however, this is conditional on there being widespread market adoption of the technology (U.S. DoE, 2014: 3).

A local fuel cell industry would enable South Africa to produce high-value-added end products for international markets, which will not only attract foreign investment, but also increase exports, at the same time decreasing imports to create a secure market for South Africa's platinum. There are also social benefits that would emanate from such an industry, bringing improvements to social environments for people of South Africa such as cheaper electricity to poor communities, among others.

> Participant B (government): "Regarding the benefits of developing a local fuel cell industry, beyond job creation it's always around securing a market for platinum, because it's only in South Africa."

> Participant D (industry): "Most of the benefits of developing a local fuel cell industry in the country are linked to national objectives, so many of the national objectives are met."

As fuel cells are classified as a green technology, it will have a positive impact on the environment while also meeting national objectives. Due to the various environmental benefits of fuel cells, it has been labelled as a 'sustainable technology' (Jansen, 2016: 11). South Africa has realised the potential of this technology and is therefore driving R&D activities of hydrogen fuel cell technology (HFCT) due to the PGMs used in the technology (HySA PADEP, 2015: 11).

6.2.5 Expertise in the South African fuel cell industry

In general, findings indicate that South Africa does have the technology as well as the expertise required for a fuel cell industry, especially engineering skills. Findings also indicate that, through the HySA initiative, a pool of skills for the industry has been developed, and that there is currently nothing done internationally regarding fuel cell technology that South Africa cannot produce locally. As South Africa already beneficiates around autocatalysts, it provides the country with a supply chain infrastructure to support the fuel cell industry. However, the country needs to get the business model right, by identifying on which components the country needs to focus: either on the entire fuel cell or on certain fuel cell components that are likely to create a local market.

> Participant D (industry): "The engineering skills are all here; HySA Catalysis has produced catalysts which have been tested by global fuel cell companies and the response was that catalyst quality has been benchmarked with other global catalyst suppliers and they were interested in going into commercial contracts with them … their catalyst quality is on par; that demonstrates that we have the potential to compete on a quality and technical basis."

> Participant J (university): "There is expertise in the country, there is a supply chain to support the industry, and there's a lot of platinum".

It is clear that the country already has numerous advantages that may aid the development of a fuel cell industry. These typically include the country's experience in the demonstration and deployment of fuel cells in a range of applications, its experience in testing and developing fuelling technologies and access to technical and engineering knowledge and skills (Jones and Botha, 2014: 318).

6.2.6 Re-skilling platinum mine workers

Regarding the possibility of retraining and absorbing platinum workers into the fuel cell industry, five respondents was of the view that it is possible, but that one needs to consider where the workers come from before making such assumptions. It was highlighted that the closer you are to the rock face, the lower the skills level and the more challenging it would be to do re-skilling aimed at meeting the higher requirements of fuel cell manufacturing. A labourer working in the mining environment cannot be re-skilled to do fuel cell manufacturing, but can be deployed in the construction environment. Seven respondents agreed that most opportunities for lower-skilled workers would typically be in deployment, construction, operation and maintenance.

> Participant C (industry): “There is a possibility, but it is limited. We can’t say that if 60 000 people are retrenched in the mining industry, the fuel cell industry is going to take 60 000 people. The current global fuel cell industry has got a maximum of 6 000 people – that is direct fuel cells – and I think there is probably a three-time multiplier for indirect jobs.”

> Participant B (government): “We call it lateral migration: skills in the mining industry can be moved, so people manufacturing mining equipment can be moved into manufacturing of fuel cells. These are not new skills.”

There were respondents who believed that re-skilling will not be possible, as completely different skill sets are required and some of these workers should rather be absorbed into industry in general. Furthermore, as the fuel cell industry in South Africa is currently only starting, it is too small to absorb the number of retrenched platinum workers.

> Participant E (industry): “Retrenched platinum workers can only be redeployed in the mining industry ... it’s very difficult to make that transformation from the platinum mining context to the fuel cell context. It’s a totally different skill set.”

> Participant L (university): “I wouldn’t say just into the fuel cell industry. There are just so many of them; they should rather be reskilled into industry in general, not specifically for the fuel cell industry because it’s so small … the fuel cell industry in the country is actually non-existent at this point in time, so you cannot promise those workers that we will retrain them to go into the fuel cell industry.”

This indicates the difference in opinion of industry, as voiced by the representatives that work in these contexts, and government, whose representatives are not really experts on the industry side. This indicates the importance of a triple-helix relationship in such instances to ensure projects that are developed around the fuel cell industry actively involve the perspectives of the triple-helix players to make the most informed decisions.

6.2.7 Qualifications and skills needed for the fuel cell industry

There seems to be agreement among respondents that qualifications needed for the fuel cell industry depend on what aspect one looks at in the value chain, and it is not always university qualifications that are needed. When considering the manufacturing of components and the assembly of fuel cells, semi-skilled to low-skilled workers are required; when considering R&D in the field, high-tech qualifications and engineering skills classified as high-level skills, such as a master's and Doctor of Philosophy (PhD) degree, are required. So it depends where the focus is. The current stage of development of the fuel cell industry entails a lot of R&D work and requires semi-skilled to high-skilled people. This finding corroborated the literature stating that, as far as the growing fuel cell industry (a highly specialised research field) in South Africa is concerned, critical skills required for the beginning stages of the industry are limited to high-level science, technology, engineering and mathematics skills, such as engineering, chemistry and high-level R&D (IDC, 2013: 20; HySA PADEP, 2015: 23).

> Participant E (industry): "If you focus on the component, then it's very few high-tech people; if you look at the roll out and application of fuel cells, it's a different ball game."

> Participant C (industry): "If you're looking at R&D, it is highly skilled and highly educated; when you're looking at deployment, you're looking at your low-level and semi-skilled workers."

In addition, there are key occupations and skills required for smooth business operations. These include people in finance who understand the business model, have the know-how to get things to work and make the industry sustainable; marketing to promote fuel cells and ensure there are customers; and human resources to manage the organisation and make sure the organisation adheres to labour regulations and employment requirements.

6.2.8 Job opportunities in the fuel cell industry

As regards the job opportunities that could potentially be created through a local fuel cell industry, respondents had different views on what occupations would create the most job opportunities. It was emphasised three repondents that high-level skills would create the most job opportunities once the industry is up and running in South Africa, which would typically include chemists, metallurgists, hydrogen production engineers, electronic engineers and mechanical engineers.

Two respondents believed that as the fuel cell industry is high-tech and therefore involves a highly sophisticated process, it does not create jobs. The only way in which the industry can create jobs on a large scale is if it creates a secondary market such as a transport industry, which will increase platinum demand. This is supported by the literature stating that, although current job opportunities in the field are predominantly specialist-based (requiring high-level skills), it is believed that as the technology moves into the early phases of commercialisation, job opportunities in manufacturing and sales as well as in the deployment stage will provide the most job opportunities (Jones and Botha, 2014: 321).

If secondary markets are created, opportunities exist for original equipment manufacturers and the like. It was indicated that it is the lower-level skills, such as those of semi-skilled and low-skilled workers, that are required for activities such as the manufacturing of components and deployment; it is at this level where the most job opportunities lie. Job opportunities will be across the skills spectrum, as the industry will require workers of various skills levels for the different tasks. These findings support the literature that indicates that job opportunities will range from engineers, materials scientists and laboratory technicians, to vehicle technicians, fuelling infrastructure installers, hydrogen production technicians and truck drivers, among others (IDC, 2013: 20).

Participant H (science council): "Automation and robotisation is the way systems are going."

Findings from the above section indicates that the South African fuel cell industry is currently fragmented and mostly at an R&D stage. Industry players are still rather hesitant to embrace the development of such an industry and, until they are fully onboard, support from government through procurement will be required to manufacture the technology locally. The fuel cell industry cannot only be considered from a local point of view, as it needs to be a player in the global arena, where the fuel cell industry is currently being developed.

The technology coming through the HySA CoCs is considered globally competitive. However, although there are areas where South Africa is on par and at the forefront of technology development, the country needs to adopt a more rapid (leapfrog) strategy rather than a catch-up strategy, as the latter will not be sufficient to keep up with global fuel cell technology development and not provide South Africa with a competitive edge. Barriers to the development of a fuel cell industry in South Africa primarily pertains to market development, as the cost of the technology is currently very high. However, according seven respondents this cost will come down with further market development and adoption. It was emphasised that South Africa should import key components and develop in parallel with other countries to ensure market creation rather than spending time and money on developing technologies from scratch and not creating a market.

Although it is not always possible to pre-empt what policies are needed for innovative technologies, existing policies need to be clear on the role of fuel cells in South Africa, which is currently not the case. Qualifications required for the fuel cell industry will across the board depend on what aspect in the value chain one looks at. Similarly, once the fuel cell industry has been developed, job opportunities across the board would include those on high-level post-graduate level (R&D) right through to low-skilled levels, depending on the value chain focus.

6.3 Triple-helix dynamics taking place in the fuel cell context

This section considers the views of government, industry and the HySA CoCs on triple-helix relationships occurring within their respective contexts. Although the main focus is on the three HySA CoCs as site studies, they form only one part of the triple-helix relationship and it is therefore vital to gain insight into the view of the other two players (industry and government) in the relationship. Therefore, this section starts with findings from government entities interviewed on triple-helix dynamics, followed by findings from industry. The final part of the section deals with the findings emanating from the three HySA CoCs, including those from the respective universities where the CoCs are based.

6.3.1 Government

The DST's hydrogen and energy director indicated that triple-helix dynamics are taking place within the department's context. It was through the DST that the HySA strategy of collaboration was initiated, with the DST being the responsible government entity, the science councils and universities hosting the CoCs, and the DST also partnering with the mining industry, specifically with Implats and Amplats as co-funders of the CoCs. This HySA initiative is therefore a good example of triple-helix dynamics taking place within the local fuel cell industry.

From the DST perspective, government's role in this scenario is to coordinate and develop a strategy document based on the needs of the country and the comparative and competitive advantages for the country in the specific sector. This essentially entails developing a business case at national level, and then funding the initiative. Universities and science councils are the implementers as they develop the technology with government funding and coordination. It is a partnership geared towards the development of technology and generating knowledge, with universities, apart from creating the knowledge and conducting research, also ensuring human capacity development. Industry supports knowledge in terms of funding technology development and plays the role of potential customers. In most cases, industry players pay for the research they think would be relevant to solving their problems.

> Participant A (government): "The triple-helix model is really the model that drives collaboration, and it also effectively addresses the issues that you may come across within an emerging sector."

The DST's funding is geared towards technology development, human capacity development with a focus on master's and PhD students across the science and engineering space. The DST prescribes that a certain percentage of the project funding should be directed towards human capacity development. It is also mobilising funding internally within the department and with industry participation to co-fund the deployment of fuel cell technologies. This corroborates the literature stating that the DST is engaged in a number of activities to develop a local market for hydrogen fuel cells in the country (DST APP, 2017: 31).

The representative of the Department of Trade and Industry (dti) emphasised that networking, especially through clusters, creates a situation where everybody knows who's doing what. When you have a working relationship, you know who the key people are when you need something. A key issue raised was clashes between the mandates of different government departments.

> Participant B (government): "… even with the workshops we organise there are lessons learnt through the sharing of information between municipalities in South Africa."

Findings from representatives of government entities interviewed on triple-helix relationships indicate that they are aware of the importance of such relationships for industry development, especially for an infant industry such as fuel cells. According to the DST representative, there are triple-helix dynamics taking place within the fuel cell industry, specifically within the HySA context. In general, government representatives had a sufficient understanding of the different roles each entity should play in triple-helix relationships and of the contribution each should make toward the development of a fuel cell industry in South Africa through various initiatives. They were clear on the provision of funding to the HySA CoCs for technology development, with a portion thereof having to go to skills development (for post-graduate studies) in the CoCs. These findings act as a practical example of what government's role should be according to the triple-helix literature, which states that government should typically take the role of industry in supporting relevant research and technology transfer by setting up hybrid organisations (of which HySA and the CoCs are examples). The triple-helix literature further states that government should facilitate university-industry interactions through policy frameworks that define research and development priorities, and through the allocation of resources such as funding across these priorities – which is done in this collaboration through the DST and the dti.

6.3.2 Industry

According to Industrial Development Corporation (IDC) representatives there are triple-helix dynamics taking place in the fuel cell context, typically through steering committees, conferences, workshops, industry initiatives driven by mining houses to secure platinum, as well as government contracts from departments such as the DST and the dti. It was emphasised that, for effective collaboration, it is vital that all players involved know and understand their respective roles in such relationships. It was further noted that knowledge transfer is vital as South Africa needs to learn from current global players in the fuel cell market. Networking should also be specific and identify niche markets where the country can best compete at global level. These niche markets can typically be classified according to the application of fuel cells, such as transport and portable or stationary applications. The issue with government support, according one industry reresentative, is that nothing actionable ever comes from steering committees, which is a problem that needs to be addressed.

> Participant E (industry): "Steering committees should stop being a talk shop with no action."

> Participant E (industry): "This is an international global market of partnerships because you can't be everything to everybody in the value chain … you need to cut out where's my niche."

The Amplats representative noted the importance of triple-helix relationships, especially for developing a fuel cell industry in the country, with each entity having its own responsibilities to make it happen. All three spheres need to be present, with all three participating at a very high level. As applications differ, there are some instances where government needs to take the lead, while in other areas industry needs to drive certain projects. It was indicated that Amplats actively engages with the HySA CoCs and their PhD students.

> Participant D (industry): "Triple-helix collaborations are vital in this industry … all the stakeholders need to be present, and the greater the extent to which each one of them fulfils their responsibilities, the higher the potential to unlock the benefits from all these projects."

The Amplats representative believed that universities should conduct R&D, create knowledge, develop the skills and capacity to support industry, and create intellectual property and commercialisation – although it is not strictly the university's mandate. This finding corroborates the literature on the role played by the other party when institutional spheres take on additional roles, which in this case is when universities adopt the role of commercialising the technologies they develop. This links to the concept of entrepreneurial universities. Industry should co-fund field trials and demonstrations and through their network start the creation of a market for the products developed at universities. In this light, and realising the important work done by the HySA CoCs, Amplats currently has funding agreements with the CoCs. Industry noted that government should fund and play a role in public procurement to create the market and should ensure adequate policies to drive the adoption of these products. This directly links up with the triple-helix argument that government should provide the necessary resources such as funding and facilitate interactions through policy frameworks. Knowledge flow between university and industry ensures better products, better processes, cost-effectiveness and competitiveness. Knowledge flow to government is also vital for creating awareness of the advantages of the technology for the country, thereby driving and influencing the policymakers. Networking, formal or informal, is also important as it brings together key stakeholders who are able to influence the development of the fuel cell sector. The Implats representative indicated that the company has relationships with all the HySA CoCs, but currently formal projects only with HySA Catalysis and HySA Systems.

> Participant D (industry): “We see HySA as being very important for operations and maintenance, engineering, design, supplying of certain goods and services in the fuel cells and the fuel cell value chain, but our specific relationship with them is in the form of R&D agreements, which involves funding.”

Science councils can be seen as the bridge between universities and industry and as the Council for Scientific and Industrial Research (CSIR) has collaborative projects with the HySA CoCs, it formed part of the sample. The CSIR representatives noted that triple-helix relationships are crucial and if one of those three spheres were missing, it would not be successful. There are, however, issues such as non-disclosure as well as the signing of agreements between various entities – it is difficult enough to get a two-way agreement signed, let alone a three-way agreement. But, the belief was that, even though triple-helix relationships are difficult and complex to manage, it could be productive if done correctly. It was emphasised that government’s role is to initiate the process and give direction, while also ensuring there are national imperatives in place; universities should develop human capital and conduct initial research; while industry would typically capitalise on the research. Industry may come up with an idea and either approach government to make it happen or approach universities/science councils to help.

> Participant H (science council): “…If you are missing one or either of those three entities, it’s against what the other two are doing and would end in failure … of the three parties, industry seems to be more difficult to bring onboard”.

It was indicated by the CSIR that knowledge transfer is vital, but that nowadays people buy knowledge when they need it. An example is when HySA bought experts (with vital knowledge and skills) from abroad, although HySA is supposed to be non-competitive and facilitate a free flow of information. HySA Catalysis and the CSIR had a knowledge transfer agreement in terms of which the CoC would lead in half of the first five to seven years to develop human capital, after which the CSIR would take over and use those people to develop the products and processes. Key to this was knowledge transfer between the university and the science council. It was noted that, what was lagging as regards triple-helix relationships, was the active involvement of industry in the relationship. It was also mentioned that the CSIR ensures knowledge sharing through hosting international conferences on fuel cell technology.

> Participant H (science council): "There's a lack of understanding of hydrogen in South Africa and with a lack of understanding comes unnecessary cautions. We organised a webinar workshop where we had three international experts talk about hydrogen and its safety issues ... there were around 60 people that attended; so all these people learn from these three experts free of charge."

Industry representatives interviewed generally agreed that triple-helix dynamics are vital to develop a fuel cell industry and all these players need to participate at a high level and should clearly understand their roles in the system. It was noted that the role played by each entity in the triple-helix system changes and depends on the application. This finding corroborates the literature stating that the type of institution playing a prominent role in a joint initiative depends on the actual technology (Nelson, 1993: 15). There is consensus among industry representatives that there are triple-helix relationships happening within the HySA context. The literature indicates that, as industry starts overlapping with universities, it may incorporate university-like training and research initiatives. This is the case with Amplats, as it co-funds the HySA CoCs to support fuel cell research initiatives and the development of post-graduate skills in the field. Overall, industry representatives emphasised the importance of knowledge transfer and networking to create awareness and influence policymakers.

6.3.3 Universities (HySA CoCs)

6.3.3.1 HySA CoCs' partnerships with government entities

As the DST is the initiator and the main funder of the HySA programme, all three CoCs have a relationship with the department. HySA Infrastructure (North West University) noted that the only partnership it has with a government entity is with the DST, which is viewed as successful. Additional funding was provided by the DST for a mining infrastructure project to do research on and test the safety of fuel cells for underground mining. The project has been running for two years and should end in 2018. It was, however, stated that currently the project is not looking promising due to the university process being slow and technology outdated.

HySA Catalysis (University of Cape Town) stated it has numerous partnerships with different departments within the DST that typically all focus on creating local technology for local manufacturing. One of these partnerships focus on technology demonstrations, while another is a partnership with the DST's awareness programme. The CoC also has a good relationship with the Technology Innovation Agency, which is part of the DST but functions independently. The Technology Innovation Agency has co-funded HySA Catalysis with the DST and is about to fund the HySA Catalysis spin-off company, HyPlat, although it is still under discussion.

HySA Catalysis is in the process of developing partnerships with other government departments such as the dti, which has been initiated by the CoC's directors. Interestingly, the CoC does not have a partnership with South Africa's Department of Energy. The reason given for this, according to the CoC, is that South Africa's Department of Energy typically only looks at technologies that make economic sense and will bring about benefits to the country in the short-term; at this point in time fuel cells are not the most economical decision. The CoC is adamant that South Africa's Department of Energy needs to align, and it was noted that, although adopting fuel cells at this point in time does not make economic sense, it can become a reality with a long-term plan of doing trails and identifying problems that can be addressed through R&D. It was emphasised that, for this to become a reality, the key players (government, industry and universities) need to start working together to develop the technology and invest in an infrastructure to ensure that the infrastructure exists when the technology becomes economically viable. This emphasises the CoCs's awareness of the importance of triple-helix dynamics required for the possible development of such an industry.

Both HySA Catalysis and HySA Infrastructure emphasised that their partnership with the DST had generally been good and that they believed the department had good intentions and ambitions. HySA Infrastructure also noted that the high-end infrastructure funding they received from the DST had never been late. HySA Systems (Western Cape University) noted it had relationships with the dti, DST, state-owned enterprises, tourism and energy, and that it had never had challenges with these. This may be because these relationships are not formal partnerships. These entities typically have relationships focused only on joint technology development and are there to assist each other when needed – there is no formal contract.

Challenges faced by HySA Infrastructure during this partnership with the DST is that, although the high-end funding has never been late, the core funding is typically somewhat delayed, which is probably due to budgeting issues. It was also mentioned that the CoC sometimes struggled to meet deadlines, writing reports and getting all required information to the DST on time. Challenges HySA Catalysis is facing with this partnership is the delay in core funding, which is affecting its operations negatively. The opinion expressed by the representative of this CoC was that the DST, as initiator of the HySA initiative, had not been good in managing the relationships between the HySA CoCs. It was noted that, when putting together different academic institutions (as in the case of the HySA initiative), such institutions all had different visions and, furthermore, tended to work in areas outside their mandate. The CoC believed that, as the DST had been the initiator of the HySA initiative, it was ultimately the DST's responsibility to govern these interinstitutional problems. HySA Catalysis noted that, although the DST was getting better at it, the programme was already eight or nine years old and was still not running smoothly.

HySA Catalysis also emphasised that government departments worked in silos when it came to fuel cell development. It was stated that the dti and IDC were pushing their own goals to set up a manufacturing industry, which in some cases were to the detriment of the HySA programme, as foreign companies were incentivised to manufacture fuel cells in South Africa. Although this benefits the country in terms of job creation, it brings in foreign technology that goes against the localisation objective of the HySA initiative. The CoC highlighted, on a more positive note, that the dti had funded ISONDO, a local fuel cell company. However, the company is licensing foreign technology, which would have been fine if the HySA initiative did not exist.

6.3.3.2 HySA CoCs' partnerships with universities

As the HySA initiative consists of the three CoCs based at the respective universities, these CoCs are linked to each other. Thus, HySA Infrastructure (North West University), HySA Catalysis (University of Cape Town) and HySA Systems (Western Cape University) are all part of a bigger initiative, namely the HySA initiative. For various reason, each of these CoCs also has additional partnerships with other universities. A project in which the CoC are all collaborating is the development of a school fuel cell, with the objective of bringing all the CoCs together to build a complete fuel cell system.

Over and above the partnerships/relationships between the HySA CoCs, HySA Catalysis has partnerships with the University of the Witwatersrand. HySA Systems has additional partnerships with universities such as Tshwane University of Technology, Cape Peninsula University of Technology, Durban University of Technology, University of Stellenbosch and the University of Johannesburg. HySA Catalysis and HySA Systems have partnerships with other universities, initiated by themselves, especially where they find that other universities have the skills they lack. Both HySA Catalysis and HySA Systems also indicated that they have a partnership with the CSIR as an intermediary operating between universities and industry.

Advantages that have come from these partnerships from HySA Catalysis's perspective include having access and exposure to a multitude of skills. This happens when students who have been funded by the CoC become interested in HySA/fuel cells, resulting in their skills being absorbed into the industry as well as the CoC itself. Access to skills is also evident with the HySA Systems CoC, as it does not have an engineering department. When engineering skills are required, other universities such as Stellenbosch University are approached. How this typically works is that HySA Systems has students registered at other universities doing research for the CoC, as universities collaborate on projects for joint technology development. The CoC indicated that, from its perspective, these partnerships were rather small and therefore easy to establish, without any real challenges at that stage.

Although these partnerships provide access to a pool of skills, a challenge highlighted by HySA Infrastructure was the fact that the CoC was located at a university, with matters therefore taking longer to resolve and the location not always being a good environment for projects. This is corroborated by HySA Catalysis, who noted that some universities did not understand the urgency behind projects and the importance of projects for the CoCs as they needed to account for them.

HySA Infrastructure emphasised that universities needed to address these challenges. However, it was believed that universities were not willing to change. A challenge raised by HySA Catalysis was that industry players and government departments still viewed the HySA CoCs as being run solely by academics, which was not the case as all the CoCs were headed by global experts with industry experience.

> Participant J (university): "We are very privileged to have international fuel cell industry experts at the centres. They are compensated well, and they have left their country to try and grow the industry in South Africa."

Another challenge highlighted by HySA Catalysis was reporting on projects, specifically reporting on the utilisation of funds. There was also the issue of universities not keeping up to date with technology development, thereby hampering the success of projects, especially those that were very urgent.

6.3.3.3 HySA CoCs' partnerships with industry

All three CoCs have partnerships with industry players. HySA Infrastructure has a partnership with industry player Amplats, which was initiated from HySA Infrastructure's side. This CoC has done work on a three-year project for the development of an electrohydrogen compressor for Amplats, which ended in early 2017 due to Amplats ending its funding for all external research activities in an attempt to downscale its funding commitments. The CoC has another project with Amplats's underground fuel cell machine developer, for which it builds storage units. Amplats has made a decision to scale down considerably and, although the company is still 100% focused on underground mining, the project is now being done internally, with HySA Infrastructure being part of that process through the external contractor, as Amplats do not want to work directly with universities.

According to HySA Catalyst it has numerous partnerships with industry players. However, there are very few fuel cell companies in the country, with most of them having their own core function. As these companies have the core competence needed by the CoC, partnerships are formed with HySA Catalysis in the hope that the fuel cell industry in the country will grow or that the technology they are helping develop will be licensed. These partnerships have mostly been initiated by the CoC and specifically at director level, as industry seems to take it more seriously if it comes from that high level. The CoC usually approaches industry with the argument that the development of fuel cells holds many potential benefits for South Africa, which seems to work as it attracts business opportunities. The objectives of these partnerships with industry are to secure complementary skills so that fuel cells can ultimately be manufactured locally, and to create a footprint for fuel cells in order to create a supply chain.

> Participant J (university): "How some of these partnerships work is that we say, OK, we've developed this technology, but we need support to manufacture some of the parts. In most cases we would pay them for their services and in some cases, when their fees are too high, we ask for a discount or we show them the potential of the industry, or we develop a memorandum of understanding stating that, if they've contributed to the technology, they own some intellectual property."

HySA Systems currently has partnerships with various industry players such as Ballard, Implats, Hot Platinum, Amplats, NEDSTAC and Plug Power Inc, with joint commercialisation as objective. Usually, the CoC goes in search of projects with industry where it can demonstrate its prototypes, also looking for funding for real products that companies can use after they have provided funding to the CoC. There are instances where industry players approach the CoC, but this is very secretive, as such partnerships are often initiated by companies experiencing difficulties.

> Participant L (university): "The automotive industry has approached the centre as they are preparing for alternative systems for the internal combustion engine to electric vehicles and with batteries' range limitation, fuel cells are coming in there … and with us being the only centre working in the fuel cell mobility application space, we have a lot of those partnerships coming through."

HySA Infrastructure noted that, in its experience, industry did not want to work directly with universities. HySA Catalysis highlighted the challenge of convincing industry players to develop the technology/industry. As industry is profit-driven, convincing them of long-term benefits is often a challenge. A challenge highlighted by HySA Systems is that the CoC is a virtual organisation (mostly interacting through information technology methods rather than through face-to-face interactions), which tends to hinder business partnerships. Additionally, the CoC noted that funding is an issue, as industry does not always have the money to fund solutions for their problems, and neither does the CoC. Therefore, projects are often terminated due to a lack of funding. Invariably, if projects cannot be funded by industry or the CoC, the two team up and develop a proposal for funding from government, which is not always successful.

6.3.3.4 HySA CoCs' views on triple-helix dynamics and related concepts

The findings indicate that all three CoCs believe that triple-helix-type relationships are vital to ensuring commercialisation, and that each player has its own responsibility and role in the bigger picture of developing a fuel cell industry. For HySA Catalysis triple-helix relationships are vital as the CoC (university) requires funding (government) for the development of technology up to a certain point, after which someone is needed to manufacture (industry) the technology. Furthermore, government is seen as an important contributor to the development of a fuel cell industry by providing an enabling environment, which can typically be done by acting as trial user, by providing funding to support the industry, by incentivising industry to manufacture locally or by incentivising research funding.

In general, all the CoCs view government's main role as providing funding and acting as a first customer of the technologies being developed by the CoCs, as it has the social responsibility to generate future industry for the country and ensure local economic development. It was, however, noted that government cannot be expected to fund everything; industry should also fund and co-develop technologies, act as customers of the technology and implement the technology. The CoCs view universities as being responsible for conducting research and development activities, as well as innovating around fuel cell technology.

> Participant J (university): "Government needs to create an environment that ensures local industry and local research institutions thrive. They should not incentivise foreign companies or the purchase of foreign technologies for local markets. Government should ensure a secure supply of funding and regular access towards institutions, they need to govern research instructions well, ensuring they stick to their mandate and that funding is used for its intended purpose. A challenge is that some students funded by the HySA initiative ultimately end up going overseas, as the industry has not quite thrived here; there's not enough industry interest in the country."

According to HySA Catalysis representative, the CoC does engage in triple-helix relationships, especially through its collaboration/partnerships with HyPlat, which has also, on its own, developed industry relationships locally and internationally. It was indicated that the main objective of this triple-helix relationship was to ensure that the technologies developed are commercialised and manufactured locally, with intellectual property rights leading back to the CoC.

HyPlat's objective is to create business and jobs and, from government's side, the objective is to create benefits for the country from platinum beneficiation and the creation of jobs. The CoC strongly believes that industry should be incentivised to participate and be willing to contribute resources with the expectation of a return for them in the long run.

> Participant J (university): "Industry must be in some ways obliged to make sure they manufacture products with local technology and not manufacture foreign technologies here. Local industry should keep the long-term goals of the HySA programme in mind and know that, if the industry grows, they can provide jobs to the trained people coming through."

According to the HySA Infrastructure representative the triple-helix dynamics taking place within the CoC are limited. These dynamics were highlighted through the CoC's partnership with Amplats (industry) and other companies in Europe (global industry), as well as University of Cape Town (UCT) and University of Western Cape (UWC) (universities). The objective of these partnerships is to develop the technologies and systems to implement them where needed in industry.

Knowledge transfer and networking are key concepts related to the triple-helix model and are both crucial for the development of any high-tech industry, according to the CoCs. Networking and knowledge transfer occurring in various context and at various levels are seen as all-important.

> Participant J (university): "There is knowledge transfer that happens from overseas people to local people, from the leadership within the centre to students and staff, from the university that developed the technology to the manufacturers and industry as well as to end users of the technology. There's also backwards knowledge transfer when industry starts manufacturing or when end users start using the technology. You find limitations with the technology and it ultimately feeds back into the HySA centres".

As knowledge transfer is important to HySA CoCs, they all provide bursaries to many post-graduate studies, from master's to post-doctoral level, in the hydrogen fuel cell field, thereby contributing to skills development. The students concerned work on different aspects of hydrogen to create a local knowledge base. HySA Infrastructure often also funds final-year projects when the projects are related to the CoC's focus on fuel cell technology. Through funding post-graduate students, the CoCs facilitate skills development, increase innovation and technology development, and thereby contribute to the knowledge to be shared in order to grow the industry. HySA Systems indicated that it is transferring knowledge to local industry, which is helping to develop a local supply chain. It also does commissioned research for industry, in which instances the industry partner is funding part of the research. HySA Infrastructure emphasised that it was involved in the creation of new knowledge, albeit at a slow pace.

An example of new knowledge that is currently being created by the CoC through projects that no one in the industry is looking at, is the safety of fuel cells underground, while everyone else is looking at the functionality of the technology underground. This is creating new knowledge, which in turn is creating awareness.

> Participant K (university): "The issue is that no one wants to take fuel cells underground because they believe it's not safe. We say we'll prove that it's safe and that's something no one else is looking at."

Knowledge transfer is closely linked to networking, which is vital to ensure everyone is aware of other activities in the field to avoid duplication. According to HySA Infrastructure, it engages in informal networking, for example when universities in Switzerland and Canada were visited. The CoC also undertakes tours to the Botswana Energy institute on a regular basis.

HySA Catalysis emphasised that networking should take place on a continuous basis. There is a need for constant communication with government, industry and research groups throughout the country to create an understanding of everyone's role and also to have a vision for the establishment of a truly local industry. HySA Catalysis provided the example of UCT, which does not have all the expertise needed for hydrogen fuel cell research projects. Typically, at the concept stage the CoC would look across the country for the needed expertise and would contact them directly. Alternatively, the CoC would, through networking at conferences, initiate a discussion or project with people in the industry who have the required skills. As the CoC receives major funding from the DST, once it comes up with a good idea for a project, it will use those funds for a substantial portion of the project. The main objective of these partnerships achieved through networking is to increase the effectiveness of research projects and to make research more advanced through partnering with entities that have the expertise and facilities that the CoC lacks. Generally, the partnerships all focus on creating a bigger footprint for fuel cells in South Africa.

> Participant K (university): "Networking is important … in the mining project that we are busy with, we are part of the international network which includes the Canadian government and some universities in the U.S. and Australia. As it's a new market and new field, everyone working independently makes no sense, because you're going to repeat the work. All work done by the Canadians they have shared with us so we don't repeat it and rather improve on what's been done."

Networking is key for HySA Systems as this is how it gets funding for its projects as well as customers for the products. The CoC is of the view that there is currently not a lot happening in the informal networking space, especially with platinum group metal producers.

6.4 Summary

Through the findings highlighted above it is clear that, generally, increased platinum beneficiation is viable. However, it needs to be considered on a case-by-case basis, taking the various market forces as well as the global context into account. Currently, the South African fuel cell industry is fragmented and positioned at the R&D stage. The technology developed through the HySA CoCs is globally competitive and expertise in the local fuel cell industry is developed continuously.

As far as technology development is concerned, South Africa is at the forefront in some instances, while in other instances the country needs to adopt a leapfrog strategy to catch-up adequately with fast-moving global technology development. As the cost of fuel cell technology is high, South Africa needs to facilitate market development to lower the cost. Existing policies for fuel cell technology need to be clear about the role of the technology in the country. Once the industry has taken off in South Africa, high-level research-type skills to lower level skills such as driver skills will be needed across the board, depending on what stage of the value/supply chain one looks at.

As regards triple-helix relationships in the South African fuel cell context, government is aware of the importance of such relations for industry development as well as the roles of each entity in such relationships. It is evident that triple-helix dynamics are taking place to some extent in the HySA initiative. Within this context, the DST, as the initiator of the programme, provides funding support to the CoCs for technology development, with the stipulation that a portion of this funding should go to skills development at a post-graduate level in the fuel cell field. Industry players linked to the HySA CoCs agree that triple-helix dynamics are vital for developing a fuel cell industry and that players should all participate at a high level and have a clear understanding of their roles in the relationship. Industry is also aware of the importance of knowledge transfer through such relationships with a view to creating awareness and influencing policymakers. Universities, in the form of the HySA CoCs, all note that triple-helix relationships are crucial. However, although the CoCs indicated the existence of such relationships in their contexts, findings indicate that most of the partnership/relationships mentioned are two-way relationships. Therefore, although there may be some form of triple-helix relationships in the contexts of the CoCs and from their perspective, these relationships are occurring on a continuum, ranging from weak to strong triple-helix relationships. This will be discussed in more detail in the concluding chapter.

SECTION D: SYNTHESIS

CHAPTER 7: DISCUSSION AND CONCLUSIONS

This aim of this final chapter is to answer questions raised at the beginning of the study by discussing key themes that emerged from findings in the previous chapter. With this aim in mind, the chapter firstly highlights the purpose of the study, followed by the research questions to be answered. Thereafter, the chapter considers findings on the challenges the Hydrogen South Africa (HySA) centres of competence (CoCs) have experienced throughout their partnerships, which hamper the development of triple-helix dynamics needed to possibly develop a local fuel cell industry in the country, as argued by this thesis. Based on the findings, the chapter concludes with a recommendation that the state of triple-helix partnerships in the fuel cell industry could be measured more accurately against a continuum of triple-helix relationships, ranging from weak to strong.

This thesis argues that, although South Africa is globally the richest country in terms of platinum ore, it is not utilising this resource to its full potential, importing finished products made from its own raw-platinum exports. To reduce the amounts of raw-platinum exports and tap into the numerous benefits of producing platinum products locally, the country needs to identify new industries that utilise platinum on a global scale. Based on this assumption, the fuel cell industry was identified as an industry where South Africa can potentially beneficiate its own platinum into final products for the local and global markets. However, the industry first needs to be technologically developed in the country to reap the success. This thesis argues that, to facilitate the possible development of a local fuel cell industry in South Africa, there needs to be knowledge transfer between all three triple-helix spheres. Therefore, this thesis looks at the extent to which triple-helix dynamics are happening in the current South Africa fuel industry, specifically focusing on the HySA CoCs as site studies.

The research questions that had to be answered through the discussion were:

1. What triple-helix dynamics are taking place in the fuel cell industry/context in South Africa?
2. Who are the main players on the side of university, industry and government in the fuel cell industry?
3. What advantages and challenges have presented themselves through these triple-helix partnerships?

Findings from the HySA CoC site studies point to numerous challenges that in turn hamper the development of formal triple-helix dynamics needed for the possible development of a local fuel cell industry. The challenges experienced include the current lack of demand to support a local fuel cell industry; funding issues; triple-helix entities generally operating in silos; different time perspectives; the absence of taking the role of the other; and finally, the prevalence of two-way interactions instead of formal three-way relationships.

7.1 Challenge 1: The current lack of demand to support a local fuel cell industry

As with any new technology on the market there needs to be demand for the product to ensure its success. Findings indicate that there is currently a limited demand for fuel cells in South Africa, which demand is vital to support the development of such an industry that is currently at a research and development (R&D) stage. The findings indicate that numerous factors may contribute to the current limited demand for the technology. These factors typically relate to the cost, industry uncertainty, industry adoption, competing technologies and a lack of awareness and understanding of the technology.

As the South African fuel cell industry is small and mostly at an R&D stage, it is perceived by many professionals in the field as almost non-existent and with an uncertain future. This leaves industry hesitant to embrace and invest in the development of the sector, not knowing where it is headed. Findings indicate that the HySA CoCs find it challenging to convince industry players to develop the technology/industry, mainly because industry is profit-driven. This poses a challenge for market development, as industry plays a vital role in establishing technology awareness to create the demand. The high cost of fuel cells and cheaper alternatives further deter industry from adopting or investing in the technology. However, as has been the case with other technologies, comprehensive market development and demand with extensive industry support have brought down the cost in other contexts. Significant market development is therefore necessary with a view to reducing the cost of fuel cells so that industry will start investing in this technology. Acquiring such investment and support from industry clearly poses a challenge.

With the high cost of fuel cells, cheaper alternative power technologies such as batteries and solar are mostly used. However, unlike fuel cells, these power technologies do not provide power on a continual basis; batteries need to be charged often, while solar devices charge only during the day, with the efficiency dropping during rainy and cloudy days. Therefore, despite the high cost of fuel cells, they are the better alternative and it is hoped that, through market adoption the cost will be reduced. Public awareness is also key to creating the demand needed to support the local fuel cell industry. Through increasing public awareness about, and educating people on, the advantages and disadvantages of fuel cell technology compared with those of other power technologies sector players will be able to make informed choices. Typically, as fuel cells are a green technology with numerous advantages over other power technologies, they are likely to create demand for the product, provided there is a reduction in cost, which is the main limitation when compared with other power technologies. However, although there are fuel cell demonstrations taking place at various locations to create public awareness, sufficient demand is not being created due to key institutions not collaborating effectively.

South Africa would benefit from adopting the practices from countries with successful fuel cell industries such as Germany, the United States (U.S.), South Korea and Japan. Germany advanced their fuel cell industry through funding, R&D efforts and industry support by means of active investment in the promotion and expansion of a hydrogen infrastructure to ensure a sustainable economic market. The fuel cell industry is continually advanced though collaboration between government, fuel cell manufacturing companies and specialised R&D institutes.

Common factors highlighted in the U.S. as having facilitated the development of its fuel cell industry include the belief of government that the country has the capabilities to innovate around fuel cell technology, which may lead to patents and new products, and a strong drive by government and environmental agencies to adopt green technologies, typically by providing funding to facilitate demonstrations and early-market deployments. Also key was the presence of researchers at state universities, laboratories and in established industries, who have been able to drive fuel cell innovation and product development. More crucial factors were partnerships that comprised of government, industry and university working together on education and outreach, developing vision plans and roadmaps, and representing and promoting the state’s fuel cell industry. In addition, the U.S. has numerous policies in support of the development and deployment of fuel cells, while state agencies provide funding, grants and low-interest loans to fuel cell companies and researchers.

Japan’s Ministry of Economy, Trade and Industry released a hydrogen fuel cell strategy roadmap to introduce and expand hydrogen and fuel cell technologies in the country. Japan’s New Energy and Industrial Technology Development Organisation, NEDO, receives funding from government and disperses it between grants for universities and subsidies for private companies focusing on fuel cells to support R&D activities around cost reduction and the improvement of durability and performance. In South Korea, government policies continually support the further expansion of fuel cells. Foreign fuel cell manufacturers are subsidised through a R&D tax credit programme that reduces import duties on equipment.

7.2 Challenge 2: Funding issues

Funding is vital, especially when a new technology or new products are at an R&D stage. The HySA CoCs are mostly funded by the Department of Science and Technology (DST) and although in most cases the funding received is sufficiently on time, there are instances where funding is somewhat delayed, which affects business operations negatively. Findings indicate that, when compared globally, funding received by the HySA CoCs from government is significantly less than in the case of international projects with the same scope. Rather than developing a new technology from scratch with a limited budget, South Africa should import a key fuel cell component and develop in parallel with other countries to ensure market creation locally.

Related to insufficient funds being available for large research projects in this field, is that often neither industry nor the HySA CoCs have funds to solve industry problems. There are instances where industry is faced with technological problems and they approach the HySA CoCs are approached to help with possible solutions through R&D projects. These projects range in scope and require extensive funding to be completed. Often such projects have to be terminated due to a lack of industry and CoC funding. Another alternative being pursued is industry, in collaboration with a CoC, developing a proposal for government funding, but this not always successful.

7.3 Challenge 3: Triple-helix entities operating in silos

The idea behind triple-helix dynamics is that universities, government and industry should work together across their traditional boundaries to share their knowledge and enable innovation. The HySA initiative, based on its triple-helix-type relationship between the DST, CoCs and respective universities, was selected as a case study of how triple-helix relationships in the fuel cell context function. As the DST, HySA Infrastructure, HySA Catalysis and HySA Systems are said to collaborate through the HySA initiative to develop a local fuel cell industry in South Africa, the communication channels between these CoCs were expected to be open, allowing for each roleplayer to work collectively towards the same goal.

However, the findings indicate that this is not necessarily always the case. Five respondents from the HySA CoCs, industry and government saw the current fuel cell industry as fragmented, explaining that activities around fuel cell development mostly happen in isolation and that entities do not always share their work with each other to further the industry. Although the CoCs and universities are brought together under the HySA initiative to collaboratively further the fuel cell industry, it was indicated that communication and collaboration between the CoCs are not what they should be. It was also noted that universities generally have different visions and tend to work in additional areas outside their mandates.

The CoCs need the DST to manage the relationships between them better to ensure the initiative remains on track. This has not been the case and has resulted in the initiative not running smoothly.

Government departments work in silos when it comes to fuel cell development and the separate mandates often clash. The non-alignment of work being done by the various departments is clear from the fact that, while the DST's HySA initiative is working on developing a local fuel cell industry, the Department of Trade and Industry (dti) seeks to set up a manufacturing industry, incentivising foreign companies to manufacture fuel cells in the country. This misalignment of government departments undermines DST's efforts and hinders market development. The South African Department of Energy, a key government player for driving the adoption of fuel cell technology (as an energy technology), currently does not have partnerships with any of the HySA CoCs, because it will only consider fuel cell technology when it becomes economically viable. However, such a technology requires a long-term approach to ensure the development of an infrastructure and market so as to be ready when the technology becomes economically viable. This clearly highlights the misalignment between the DST, which is strongly driving fuel cells for local manufacturing; the dti, which is driving foreign technology and companies to manufacture fuel cells locally; and the South African Department of Energy, which is not interested in fuel cells as the industry it is not yet economically viable.

7.4 Challenge 4: Different time perspectives

Industry role players have also been noted as preferring to work on their own and not always with government or universities. There are instances where industry has had partnerships with universities through the HySA CoCs, only to move away from these partnerships because of not wanting to work with universities for various reasons. One of these reasons is that the university process is slow and that the universities/HySA CoCs are run by academics who do not understand industry. It is true that government departments, universities and industry all operate within their own timeframes, and this results in major challenges in the partnerships between them. Things take much longer at the HySA CoCs as they are based at universities, which is not ideal for urgent industry projects. What further slows down projects is that not all universities keep up to date with new technologies. The notion held by industry that the HySA CoCs are run by academics who do not understand industry is not accurate, as in reality these CoCs are run by international industry experts with significant insights and knowledge to grow the industry in South Africa. This highlights the lack of communication between the entities and that industry prefers to work in isolation.

7.5 Challenge 5: The absence of taking the role of the other

With universities, government and industry mostly working in isolation, the possibility of taking the role of the other, which is key to triple-helix-type partnerships, is rather limited. There are some cases where institutions are taking the role of other institutions to some extent. HySA CoCs are taking the role of the university though training and funding post-graduate students in the fuel cell field in addition to its main responsibility, which is to conduct research in the fuel cell field. This often leads to these students being absorbed into either the CoCs or the fuel cell industry. Universities linked to the HySA CoCs are often engaged in the commercialisation of fuel cell technology coming though the CoCs. However, industry is of the opinion that universities should not take part in commercialisation activities and should rather focus on their main task, which is to teach. Through the discussion above, it seems clear that extensive work is needed to get all triple-helix institutions in the fuel cell industry onboard to work together to possibly further industry.

7.6 Challenge 6: Prevalence of two-way relationships

This thesis argues that the possible development of a local fuel cell industry in South Africa requires knowledge transfer between triple-helix spheres (three-way relationships), comprising government, universities and industry. As previously mentioned, the HySA initiative was identified as a key programme in which triple-helix-type relationships occur, and was therefore selected as a case study for this thesis. However, as will be shown below, findings indicate that the partnerships taking place within these CoCs are mostly two-way partnerships.

Funding from DST is not directed only at R&D activities undertaken by the CoCs around fuel cell technology; it is also used for post-graduate bursaries to enable skills development in the field for the benefit of the industry. This indicates triple-helix-type relationships within the HySA context, with DST being the main funder, the HySA CoCs functioning as R&D institutes for industry, and the universities enabling skills development through the CoCs. However, just because the DST initiated the HySA and is funding the CoCs, it is not automatically an active partner in the partnerships between the respective CoCs and other industry players. Most HySA CoC's partnerships are between the CoCs and either directly with industry, government or other universities (two-way partnerships), but not with all of these at the same time for a specific project.

In addition to their partnership with the DST as their main sponsor, the three CoCs have other direct partnerships with other government departments, industry players and universities. Although HySA Catalysis has a triple-helix-type partnership with HyPlat (the spin-off company they developed), it is mostly engaged in two-way partnerships. It has partnerships with industry players and is currently busy developing a partnership with the Industial Development Corporation (IDC). In addition to having a partnership with North West University (NWU) through the HySA initiative, the CoC also has partnerships with numerous other universities, which are two-way partnerships.

HySA Infrastructure does engage in triple-helix-type partnerships, but only to a limited extent. The CoC indicated that there are various two-way relationships, typically between it and government, or between it and industry. HySA Systems has numerous partnerships with universities as well as with science councils, but also to a limited extent. It often collaborates with other local universities on projects for joint technology development as well as with industry for the joint commercialisation of these technologies. As far as its partnership with government is concerned, it indicated that it typically takes the form of a relationship and not a formal partnership, and is also based on joint technology development. Apart from the partnerships in the context of the HySA CoCs, the partnerships relating to the fuel cell demonstration project discussed in Chapter 5 were also mostly two-way collaborations between only government and industry players.

Therefore, although government, industry and all three HySA CoCs are aware of the importance of triple-helix-type relationships for knowledge transfer through networking across boundaries, the findings show that collaborations in the South African fuel cell industry are weak triple-helix-type relationships based primarily on two-way partnerships. In view if this and in an attempt to gain a better understanding of the extent of triple-helix relationships in the South African fuel cell context, it is recommended that such partnerships be measured along a continuum (Figure 5) from weak to strong triple-helix dynamics.

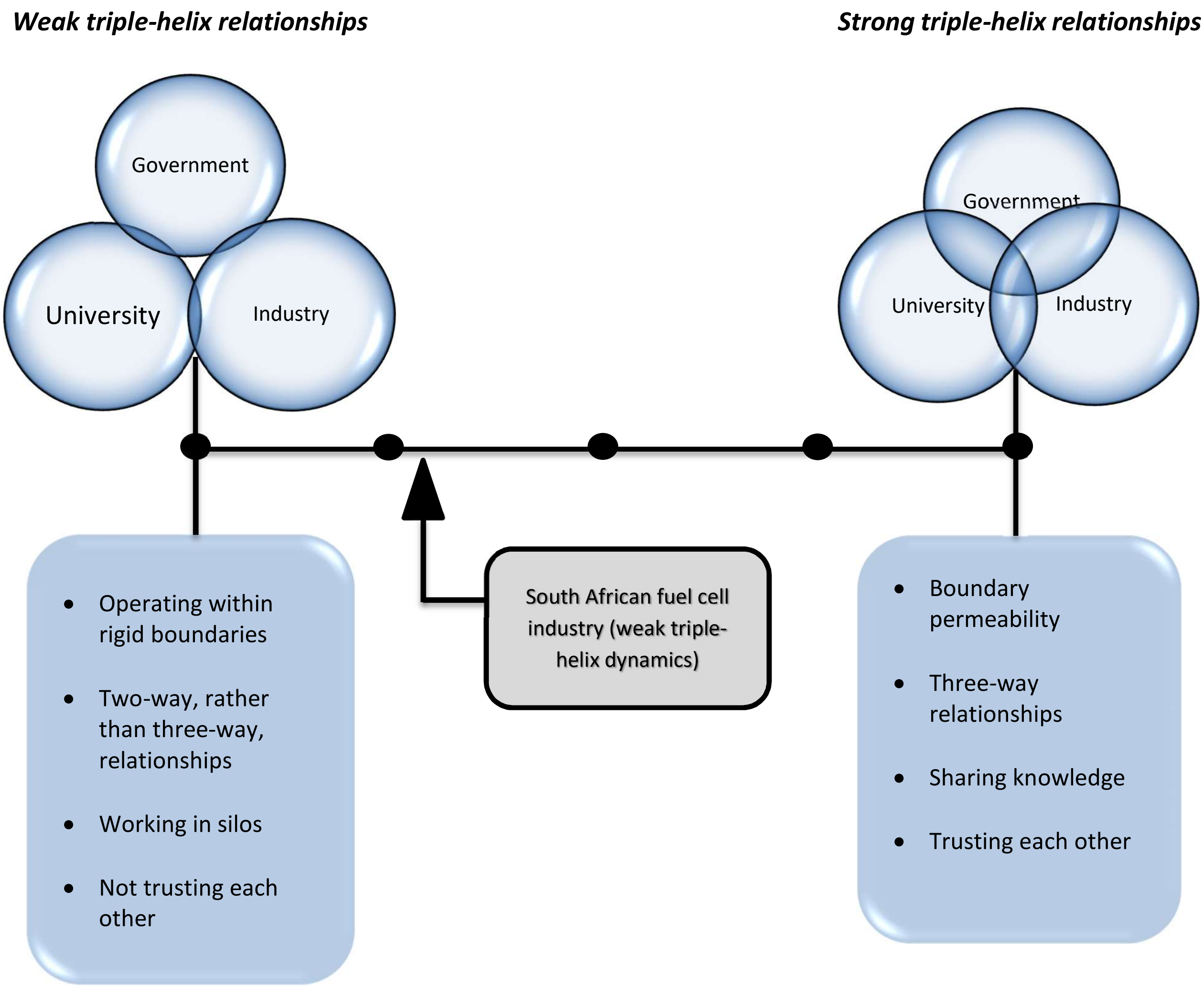

Figure 5: Triple-helix continuum (Thesis recommendation)

Referring to Figure 5 above, weak triple-helix relationships are characterised by numerous factors, such as operating within rigid boundaries; operating as silos; low levels of trust between institutions; and having only two-way partnerships. Although these factors are mentioned separately, they are closely related and typically interconnected. In other words, it may be that institutions prefer to work independently because of the low trust between them, thereby ensuring that they do not blur their traditional boundaries. This results in them operating in silos, not sharing knowledge with each other and often leaving them unaware of new developments in the field. As institutions prefer to work in silos in the context of weak triple-helix relationships, these partnerships are mostly two-way. And as there is no sharing of knowledge and responsibilities, a triple-helix relationship would be too onerous, resulting in institutions opting for a more manageable two-way relationship.

On the other side of the spectrum is the ideal triple-helix theoretical model, namely strong triple-helix relationships, which are characterised by boundary permeability; a high-level of trust between institutions; and strongly established three-way institutional partnerships. It may be that the high-level of trust between the triple-helix institutions allows for boundary permeability. This means that institutions operate across blurred traditional institutional boundaries, allowing for free knowledge flow, which often leads to these institutions taking the role of the other. Strong triple-helix relationships are characterised by robust three-way partnerships between institutions that collaboratively work towards the same objective. However, in practice it seems that most triple-helix relationships fall somewhere between the two extremes of strong and weak, which is also the case with the South African fuel cell industry.

The fuel cell industry is currently characterised by mostly two-way relationships, there is a high degree of mistrust between key institutions in the field, and the limited boundary permiability leads to the evident miscommunication between institutions, resulting in them being misinformed about each other's activities, structures and developments in the field. When considering these factors of the current fuel cell industry against the proposed triple-helix continuum, the South African fuel cell industry may therefore be classified as having weak triple-helix relationships. The triple-helix continuum proposed in this thesis goes beyond the fuel cell context and may also assists with analysing the extent of triple-helix relationships in other contexts and industries.

7.7 Conclusion

In conclusion, this thesis identified fuel cell technology as a potential new market that, if successfully developed locally, could increase platinum demand and result in economic growth for the country. The thesis argues that the success of the development of a local fuel cell industry could be achieved when there are strong triple-helix collaborations between government, universities and industry to facilitate knowledge sharing and innovation around fuel cell technology. Should these institutions' boundaries become blurred, they will increasingly work together, resulting in them "taking the role of the other". This refers to when any one of the institutions take up an additional role that is traditionally associated with a different type of institution. This would occur, for example, when universities take part in commercialisation, which is typically associated with industry; when industry starts incorporating university-like training and take part in research initiatives associated with universities; and when government acts as a customer for fuel cell technology, which is typically associated with industry, to ensure demonstration of the technology.

In an attempt to understand the extent of current triple-helix-type relationships in the fuel cell field, the HySA initiative was selected as a case study. Findings indicate that, although such relationships are taking place within the fuel cell industry and the HySA CoCs, these are mostly two-way partnerships. Based on this, the thesis recommends using a triple-helix continuum, ranging from weak to strong triple-helix relationships, against which the extent of such relationships can be measured more accurately. In terms of such a continuum, the current fuel cell industry in South Africa can be classified as consisting of weak triple-helix relationships, as illustrated in Figure 5.

These weak triple-helix relationships may be attributed to various single or combined factors. It may typically be due to the fuel cell industry being at an R&D and demonstration stage as a result of the partnership challenges highlighted in the findings. Challenges that need to be addressed to enable stronger triple-helix relationships include that government departments need to be better aligned and better coordinated to manage activities around fuel cells more efficiently, and that all three triple-helix institutions (government, universities and industry) should put aside their differences and stop working in silos. The latter challenge relates especially to industry players, which should become more willing to work with the other institutions, sharing their expertise in manufacturing these technologies, which may benefit not only them, but also the whole country in the long run. To sum up, these triple-helix players in the fuel cell industry should not only acknowledge that triple-helix relationships may facilitate the development of the fuel cell industry in South Africa, but should also actively start engaging and developing partnerships with each other to this end.

Through the practical case study conducted in this thesis, a major limitation to the triple-helix model was identified. It was found that the model itself is an ideal-type theoretical abstraction that is not always reflected in actual conditions. The triple-helix theory does not always account for the actual opportunities and constraints related to collaboration in the real world. This is evident in this thesis, as the theory did not capture the plurality of relationships, which are most often two-way formal partnerships. Therefore, although the triple-helix model is valuable as an abstraction, it loses some of its precision in translation into real-world conditions. This thesis recommends the use of a triple-helix continuum model, which would more accurately account for the beginning stages of triple-helix interactions all the way through to strong triple-helix partnerships.

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