Building the hydrogen economy through niche experimentation and digitalisation

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Abstract

Purpose – Hydrogen fuel cells could play an important role in meeting the challenges of the Two Degrees Scenario. The purpose of this paper is to review the development of this technology in South Africa with the aim of understanding how the country can transform its existing socio-technical systems and act to support a hydrogen-based technological innovation system (TIS).

Design/methodology/approach – A mixed methods approach has been followed in this study. Secondary data analysis was used initially to build a profile of South Africa's present energy system, followed by a stakeholder survey of the emerging hydrogen economy. Respondents were selected based on a convenience/snowball sampling approach and were interviewed using a semi-structured questionnaire, covering opportunities for South Africa in the global hydrogen economy; sources of competitive advantage; the present phase of development; the maturity of each function and the main weaknesses within the TIS; and finally the appropriate policy instrument to remedy the weakness and/or maximise opportunities for local companies.

Findings – The research has shown that the hydrogen economy is still at a pre-competitive level and requires ongoing government support to ensure an energy transition is realised. In particular, it is important that niche experimentation, a proven strategy in respect of successful sustainability transitions, is further pursued. Importantly, the net cost of hydrogen-based transportation, which is still several times larger than the cost of transport based on the internal combustion engine (ICE), must be reduced, especially in the key applications of public transport and underground vehicles. Furthermore, the development of digital technologies to manage supply fluctuations in energy grids must be accelerated.

Originality/value – The South Africa economy will be severely affected by the replacement of the ICEs with battery electric vehicles due to the country's reliance on ICEs for platinum demand. Fuel cells represent a new market for platinum but the hydrogen TIS is still at a vulnerable point in its development; without policy support, it will not contribute to a successful socio-technical transformation, nor provide an alternative outlet for platinum.

Keywords Government policy, Digitization, Green manufacturing

Paper type Research paper

1. Introduction

Global energy systems continue to rely on the non-renewable resources of coal, oil and natural gas, as shown in Figure 1. Collectively these three feedstocks account for 87 per cent of the global carbon dioxide emissions, with the latter now exceeding 35 trillion metric tonnes per year (Decourt *et al.*, 2014). Energy usage is spread over all economic sectors but the major emissions of carbon dioxide arise from electricity production (42 per cent), transport (23 per cent) and industry (19 per cent) (IEA Statistics, 2015).

It is widely acknowledged that unprecedented levels of carbon dioxide emissions are causing climate change. The existing concern and impending crisis for global ecosystems has led to the adoption of the Paris Agreement which requires all ratifying countries to contain and reduce their greenhouse gas emissions with the goal of peaking such emissions "as soon as possible" and continuing the reductions thereafter, thereby keeping global temperatures from rising no more than 2°C by 2100, referred to as the Two Degrees Scenario (2DS), with the ideal target being a rise of not more than 1.5°C (Robbins, 2016).

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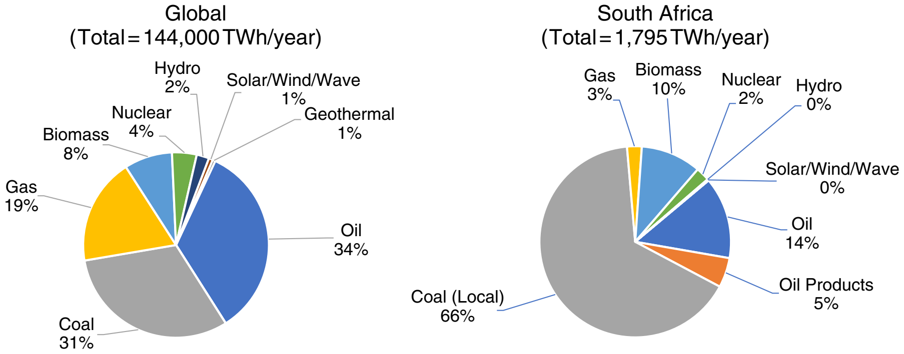


Figure 1. Global and South African sources of energy (2014)

Meeting the 2DS goal will be impossible without the decarbonisation of the transport (liquid fuels) and electricity sectors; accordingly European Union targets on emissions for 2050 will require a 95 per cent decarbonisation of road transport (McKinsey & Company, 2010). Hydrogen fuel cells can play a vital role in the attainment of these targets, supporting the mitigation efforts related to minimising climate change and raising energy security (International Energy Agency, 2015). Furthermore hydrogen fuel cells, together with technologies for the transformation of power-to-gas and power-to-liquid fuels, can be used alongside wind and solar systems as a means of addressing the intermittency of these two technologies, storing surplus power and facilitating the decarbonisation of the chemical industry (Plessmann *et al.*, 2014).

Apart from the potential role of hydrogen fuel cells in supporting the transition of energy systems to renewable resources, the technology can also be used to reduce the levels of dangerous pollutants in the urban environment which arise from the use of diesel in public transport. Following studies done in the 1980s on particulate emissions from diesel exhausts (McClellan, 1987), there has been growing pressure to phase out the use of diesel in buses and trains. For instance, in 2016 the Mayor of London, at the unveiling of the city's first double-decker hydrogen bus, announced that all buses would become zero emission by 2020 (Greater London Authority, 2016). Other 11 major cities, including New York, Los Angeles, San Francisco, Amsterdam, Copenhagen and Cape Town, have similarly agreed to phase out their procurement of pure diesel buses by the end of 2020.

Although the market is actively looking for technological solutions to the environmental challenges, hydrogen fuel cells are still at an early stage of development and not yet economic in either of the abovementioned applications (intermittency and public transport). The difference between the technology's present level of maturity and the required price points is substantial and significant support will be required across a range of functions in order to ensure that hydrogen can play a role in global energy systems. This paper reviews the hydrogen economy in South Africa in order to understand how the country can act to support a new hydrogen-based technological innovation system (TIS) that will be essential to meet the goals of 2DS.

In the first section, fuel cell technology is briefly described and proportioned, followed by description of the South African hydrogen economy and an introduction to the theory of TIS, as developed by Hekkert *et al.* (2011). This theory, together with a comparison of the techno-economic data for key applications of the existing technologies, is then applied to an analysis of the hydrogen economy leading to an identification of the main weaknesses within the South African system. Finally, the paper concludes with a set of recommendations on how niche experimentation could be used to facilitate the entry of hydrogen fuel cells into the transport and energy sectors.

2. Background material

2.1 Overview of hydrogen fuel cell technology and costs

The core technology of a hydrogen fuel cell is the use of a catalyst (often platinum) to convert gaseous hydrogen into electricity. The hydrogen, normally stored under pressure at 70 MPa, is delivered to the anode of the cell where it releases electrons in the presence of the catalyst and migrates across the electrolyte as protons. At the cathode, these protons combine with oxygen anions, arising from the reduction of oxygen in air, also in the presence of a catalyst, to form water (see Figure 2).

There are many different types of fuel cells including the Proton Exchange Membrane Fuel Cell (PEMFC), the Direct Methanol Fuel Cell, the Phosphoric Acid Fuel Cell (PAFC), the Alkaline Fuel Cell (AFC) and the Solid Oxide Fuel Cell (SOFC) (Edwards *et al.*, 2008). The cells differ according to the type of electrolyte and the material of construction at the anode/cathode, as shown in Table I. The most dominant type for the smaller mobile (transport) applications is PEMFC, whereas PAFC is preferred for larger, stationary systems. Although SOFC systems were more popular relative to PEMFC in 2013/14 due to Japan's large-scale programme for the use of SOFC in combined heat and power applications, this segment of the market has diminished significantly and PEMFC now has a majority market share at close to 80 per cent of global shipments of fuel cells.

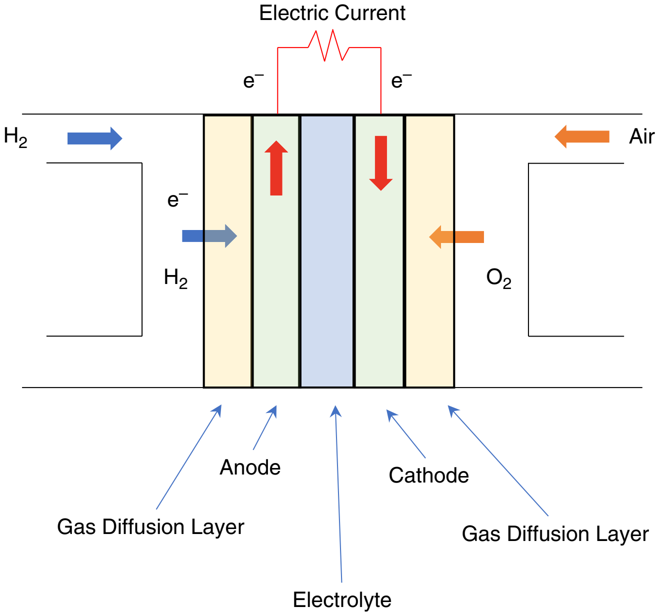


Figure 2. Schematic of hydrogen fuel cell

Fuel cell type	Typical capacity (kW)	Efficiency (%)	Investment cost ($/kW)	Lifetime (h)	Maturity
PAFC	< 11,000	30–40	4,000–5,000	30,000–60,000	Mature
PEMFC (transport)	80–100	45–50	500–750	< 5,000	Early market
PEMFC (stationary)	200–2,000	50–55	3,000–4,000	< 60,000	Early market
SOFC	< 200	50–70	3,000–4,000	< 90,000	Demonstration
AFC	< 250	50	200–700	5,000–8,000	Demonstration

Source: International Energy Agency (2015)

Table I. Main types of hydrogen fuel cells

Capital and operating costs for fuel cells have declined over the last two decades, although the technology is still expensive relative to fossil fuels. The costs of electrical energy from various sources are often compared using the levelised cost of energy (LCOE), values for which are published by several agencies and companies including the US Department of Energy and Lazard. The latter's reports are available on an annual basis, cover a wide range of technologies including solar photovoltaic (PV), solar thermal, fuel cells, geothermal, wind, biomass, diesel, gas, nuclear and coal (Lazard, 2016) and are mostly reported in terms of ranges given that the LCOE values are context specific, and depend on various assumptions. The latest LCOE values estimate PV costs at \$49–\$62/MWh and fuel cell costs at \$106–\$167/MWh (Lazard, 2016).

Within the various fuel cell technologies, PEMFC has become a leader within the transport sector, resulting in a growing demand for the technology, and the positive projections for fuel cells in general based on the demise of the internal combustion engine together with strong growth of either battery or fuel cell electric vehicles (Sassams and Leaton, 2017).

However, technology costs are critical for the future of the fuel cell electric vehicle. Although electrolysis (the splitting of water to hydrogen and oxygen) and the subsequent conversion of hydrogen to electrical power are well-proven technologies, the costs for each step are presently uneconomic in most applications even with a generous carbon tax. For instance, it is estimated that a tax of at least \$82 per tonne CO_2 will be required for hydrogen fuel cells to be competitive against existing liquid fuels (see Table II). The carbon tax value has been calculated based on estimates for the efficiencies and specific carbon dioxide emissions of gasoline and hydrogen, as shown in the table.

2.2 Overview of hydrogen storage, compression and distribution

Hydrogen has a high energy content per unit weight but a low per unit volume, with the result that hydrogen storage in sufficient quantities to support its use as a chemical fuel is costly. Indeed, it has been noted that the safe and cost-effective storage of hydrogen is a major barrier to the widespread adoption of hydrogen as an energy carrier and the subsequent development of a hydrogen economy (Broom, 2011).

Typically, hydrogen is stored as a compressed gas under high pressure, although many other systems have been investigated including liquid hydrogen (cryogenic), microporous media (such as nanotubes), hydrides, metal organic frameworks and low pressure tanks (Barthelemy *et al.*, 2017; Durbin and Malardier-Jugroot, 2013). However, this research has not yet yielded the desired outcomes in terms of cost and safety, with the estimated prices of on-board systems being about \$12–\$16/kg (Niaz *et al.*, 2015), which is about an order of magnitude higher than the equivalent liquid fuel systems (Amos, 1998).

The most attractive approach to hydrogen distribution remains the use of a gas pipeline serving a network of refuelling stations. There are already 274 hydrogen refuelling stations, but Denmark is the only country which can offer a territorial base coverage; it is also the country with the highest density of hydrogen stations per inhabitant (FuelCellsWorks, 2017).

Parameter	Units	Internal combustion engine	Fuel cell electric vehicle
Energy efficiency (fuel to mechanical)	%	20	47
Carbon emission	kg CO_2/MWh	2,728 (includes refinery)	140
Total cost of ownership	\$/MWh delivered	134	346
Carbon tax required for equal cost	\$/MT CO_2	82	

Table II. Efficiencies and emissions for fuel cell electric vehicles vs internal combustion engines

2.3 *The South African hydrogen economy*

The hydrogen economy in South Africa is a small group consisting of the platinum producers (Anglo Platinum, Impala Platinum, Lonmin and Sibanye), two government departments (Trade and Industry, and Science and Technology), a public research institution and a number of universities. The latter are mostly collected into an initiative known as the Hydrogen South Africa (HySA) Programme, which is a research and development (R&D) programme funded and managed by the Department of Science and Technology. Its goal is to develop technology for the local manufacture of hydrogen fuel cells and to create demand for the use of platinum group metals. Under the programme, three Centres of Competence have been established covering different parts of the hydrogen value chain. HySA Catalysis, based at the University of Cape Town, focusses on the development of innovative components for PEMFC stacks, including catalysts, electrodes and complete membrane electrode assemblies. HySA Infrastructure, located at North West University, develops innovative applications and solutions for hydrogen production, storage and distribution. It offers novel technology for electrochemical hydrogen compression, hydrogen storage, electrolysis linked to photovoltaic panels and methanation. Finally, HySA Systems, based at the University of the Western Cape, covers high temperature PEMFC for combined heat and power applications, and the development of complete systems including fuel cell electric vehicles and complete PEMFC stacks.

On overall representation of the hydrogen value chain in South African is shown in Figure 3. It is noted that with the exception of hydrogen transport and distribution (T&D), all components of the value chain are covered to some extent by HySA, and that there are several commercial companies active in hydrogen generation, hydrogen storage and hydrogen T&D.

2.4 *Theory of technological innovation systems*

A number of previous studies have analysed the rather complex problem of how new technologies in support of sustainability transitions can become more dominant within their respective market applications. Two approaches have been selected for this study, namely, the framework of TISs (Bergek *et al.*, 2008; Hekkert *et al.*, 2007, 2011; Markard and Truffer, 2008b) and the theoretical understanding of sustainability transitions (Markard *et al.*, 2012), in particular the concept of niche management (Schot and Geels, 2008).

The frameworks share a set of common principles as follows:

- Sectors like energy and transport can be conceptualised as socio-technical systems. Such systems consist of actors, networks and institutions (rules and standards of the system), as well as material artefacts and knowledge. The systems concept emphasises that the components are tightly interrelated and dependent on each other.

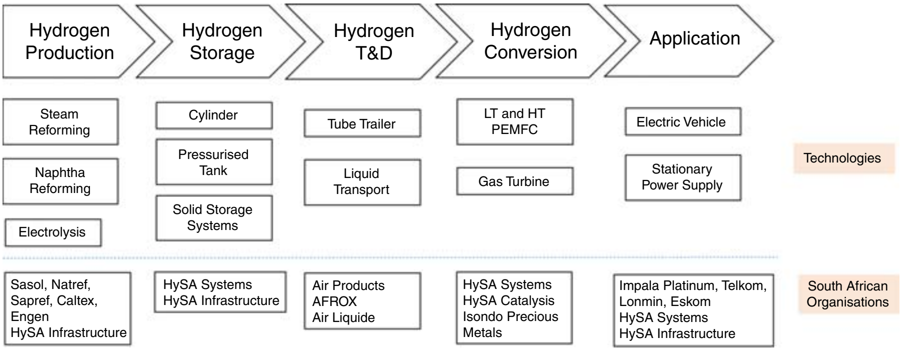


Figure 3. Components of the hydrogen value chain

- A socio-technical transition is a set of processes that lead to a fundamental shift in socio-technical systems. Sustainability transitions are long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption.

In terms of TIS theory, there are seven broad key areas that need to be addressed in the maturation of emerging innovation systems (Hekkert *et al.*, 2011), namely, entrepreneurial experimentation and production (F1); knowledge development (F2); knowledge exchange and diffusion (F3); guidance of the search (F4); market formation (F5); resource mobilisation (F6); and legitimation or counteracting resistance to change (F7) (Hillman *et al.*, 2011). F1 refers to the level of entrepreneurial activity; F2 to knowledge creation through R&D; F3 to technology transfer and diffusion; and F4 to the expectations of key actors and particularly government which will positively affect the visibility and clarity of specific needs among technology users. An example of the latter in the field of renewable energy is the long-term decarbonisation goal set by governments for their respective energy sectors. F7 refers to the creation of legitimacy for the new technology including active lobbying and advocacy by industry groups to promote the adoption of the new technology.

The role of government changes according to industry maturity, the phase of technology development and the type of technology (Wilson, 2012). For instance, in the formative phase government is required to pioneer changes in the political and regulatory context which will legitimate the industry including the removal of barriers to market acceptance. In the up-scaling phase, government support for market development through the appropriate demand-side incentives is important, whereas in the growth phase robust competition policy is more critical.

2.5 *Niche experimentation*

An additional and important role for government in the formative phase is its support for niche experiments. In the development of technologies which have significant potential to allow the preservation of public goods, as is the case of the hydrogen economy, governments are compelled to act in a way which mitigates the risk of the development. In this regard, there are a number of possible approaches of which experimentation is now the most widely used (Schot and Geels, 2008; Sengers *et al.*, 2016).

The practice of "experimenting" or "experimentation" is central to the transformation of existing socio-technical regimes to more sustainable systems. The notion of socio-technical experimentation is that society itself can be considered as a laboratory within which a "variety of actors commit to an experimental process which results in the trial and possible introduction of alternative technologies, where the latter seek to purposively re-shape social and material realities" (Sengers *et al.*, 2016).

A number of approaches have been followed in such experiments, with perhaps the most important being niche experimentation. Existing socio-technical regimes, characterised by entrenched networks of actors and institutions, form the core of present systems and are often a barrier to structural change towards sustainability. In niche experimentation, new technological niches, enabled initially by radical innovation, are created and protected from the competitive pressures of the existing socio-technical regimes. The environments within these niches allow the nurturing and co-evolution of technology, user practices and regulatory structures, and may develop into market segments. Within these spaces, co-evolution of technology, user practices and regulatory structured can take place in an experimental manner.

There are three processes which are considered to be critical for the initial protection of niche experimentation, namely, shielding (a process which holds off selection pressure); nurturing (a process which supports the development of the path breaking innovation); and empowering (a process which makes niche innovation competitive against the existing regimes). Other important aspects are social learning (a process of knowledge diffusion, sharing and linking with associated or adjacent domains), scaling up (a balancing between providing support to niche players and engaging with existing actors who have the power and resources to bring about socio-technical change). In an area of experimentation broadly referred to as transition experiments, the key processes as labelled as broadening, deepening and scaling up (Van den Bosch and Rotmans, 2008).

In summary, this study draws on two theoretical frameworks which are complementary and mutually enhancing to the development of its conclusions. In the first case, it has employs the TIS structure to both profile and critique the South African hydrogen economy, following the approach of a previous study on stationary fuel cells (Markard and Truffer, 2008a); second, it uses the theory of sustainability transitions, and particularly the concept of niche experimentation to develop recommendations for government policy and programmes. The latter is highly relevant to the case of a formative TIS, which is the present situation for the hydrogen economy. Further details on how niche experimentation can be applied within the South African context have been given in the discussion section of this paper.

3. Methodology

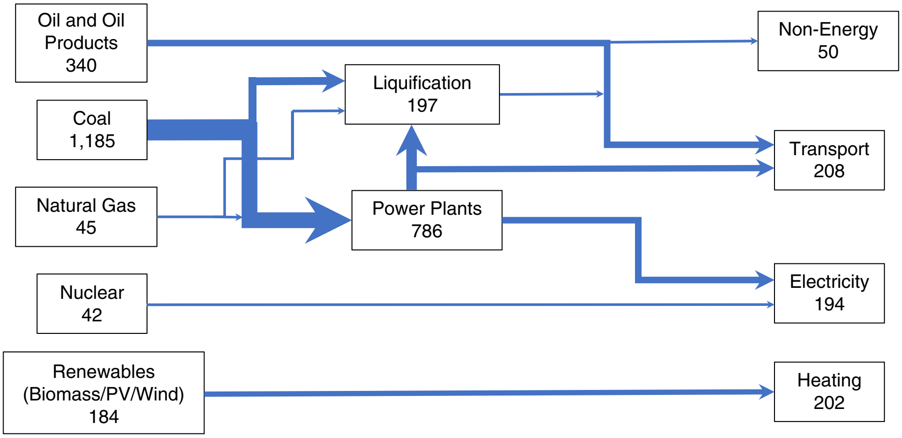
A mixed methods approach has been followed in this study. In the first phase, secondary data were analysed to build a profile of South Africa's present energy system. This phase was followed by a stakeholder survey of the emerging hydrogen economy. Respondents were selected based on a convenience/snowball sampling approach and were then interviewed using a semi-structured questionnaire, the contents of which had been previously outlined and covered a number of aspects including opportunities for South Africa in the global hydrogen economy; sources of competitive advantage; the present phase of development (pre-development, development, take-off, acceleration and stabilisation); the maturity of each function (F1–F7) of the TIS; the important gaps or weaknesses of the TIS; and finally, the appropriate policy instrument to remedy the weakness and/or maximise opportunities for local companies. The interviewees consisted of a mixture of researchers, government officials and employees of private companies.

The work was designed as an exploratory study with no attempt to be comprehensive in its approach. This method, which is broadly described as an exploratory, qualitative design using a limited number of industry experts as informants, has been followed in previously published TIS studies (Chen, 2018; Edsand, 2017; Jacobsson and Karltorp, 2013; Karltorp *et al.*, 2017). It is acknowledged that this design limits the external validity of the results and particularly the extent to which the responses can be claimed as being representative of the sector, an outcome which could be claimed in the case of a quantitative, comprehensive approach. Nevertheless, the fuel cell community in South Africa, and indeed many emerging TISs in other countries, are small communities of researchers, lobbyists, government officials and market developers who share similar views about the prospects for fuel cell technologies and its market challenges. The results of the survey are therefore considered to be sufficient in being able to develop the theoretical insights of the case study, as reported in this paper.

4. Results

4.1 Analysis of the South African energy system

Present configuration. The Sankey diagram for the South African energy supply/demand is shown in Figure 4. There are several unique features about system which are important to the overall discussion on sustainability transitions and niche experimentation, as follows:



Source: www.iea.org/sankey/#?c=South%20Africa&s=Balance

Figure 4. South African Sankey diagram (TWh; 2014)

- The system is relatively small, forming only 1 per cent of the global energy system.
- In terms of primary resources, the system is heavily dependent on coal, where the latter is 66 per cent of the total energy demand in South Africa vs 31 per cent for all countries (see Figure 1); such dependence is the consequence of both abundant local coal reserves and very limited local production of oil and gas, with more than 90 per cent of all oil, oil products and natural gas being imported.
- It has a large coal-to-liquid fuel facility which supplies about 30 per cent of the country's overall needs for liquid fuel; the existence of this facility together with the associated expertise in gas-to-liquids technology (Meleloe and Walwyn, 2016) may assist the overall transition to a 100 per cent renewable energy system, as explained in the later sections of this paper.
- Biomass is still a relatively large component of local energy resources, mainly as a result of this material being a relatively inexpensive means of residential space heating and still widely available. However, biomass is a declining resource due to overharvesting and the pressures of urbanisation accompanied by the loss of suitable agricultural land (Niedertscheider *et al.*, 2012). Biomass as a heating fuel is also highly inefficient, leading to significant carbon emissions, environmental degradation and increased disease burden (Fullerton *et al.*, 2008; Norman *et al.*, 2007).
- Solar and wind energy have historically been an insignificant proportion of total energy supply ($<$ 0.2 per cent), although this has changed since the introduction of the Renewable Energy Independent Power Producers Procurement Programme (Walwyn and Brent, 2015). Renewable resources now supply 10 per cent of the country's electrical energy requirements (Obert and Pöller, 2017).

Revised configuration based on hydrogen fuel cells. South Africa has abundant resources of wind and solar, and other studies have already shown that given the diverse climatic conditions, a national grid which is almost completely dependent on renewable resources will be possible (Bofinger and Bischof-Niemz, 2016). In other words, very high levels of renewable energy penetration within the national grid could be accommodated without compromising energy security.

However, the cyclical nature of energy generation from wind and solar will require at least one and preferably several forms of cost-effective energy storage. The need for storage will provide the ideal opportunity for hydrogen, which could serve as an energy battery and distributor, depending on the cost and availability of the hydrogen infrastructure. In the first instance, excess power from wind and solar, which will become available as the installed capacity of photovoltaic cells and wind turbines increases, can be used to produce hydrogen via (fuel cell) electrolysis. This hydrogen can then be stored and used in fuel cells for energy generation as may be required, leading to the type of system architecture as shown in Figure 5.

The new structure proposes that infrastructure for wind and solar should be at least ten times the present levels and possibly higher, depending on the actual electrical efficiencies which will be obtained as the degree of dependency on renewable resources rises. This proposition clearly has an associated cost and although low carbon emissions are desirable from a climate perspective, the cost of the transition will need to be carefully managed in order to ensure that it does not reduce the competitiveness of the South African economy.

4.2 Analysis of the hydrogen technological innovation system in South Africa

The South African hydrogen TIS was analysed using the standard structure as presented earlier, supported by hydrogen roadmaps developed by the Industrial Development Corporation (2016), Impala Platinum (Smith, 2016), the Department of Science and Technology (2008) and Department of Trade and Industry (2016). The results of the analysis are summarised in Table II.

It is clear from the table that the overall system is still in a formative phase or pre-development phase, characterised by a strong focus on knowledge creation (R&D), supported by the resource mobilisation, guidance of the search and knowledge exchange. The system has the positive properties of high-intensity applied research, the presence of several small-scale companies and some installed hydrogen fuel cell capacity. In terms of the latter, a number of prototypes and demonstration units, including electrolysers for the conversion of solar energy to hydrogen, electrochemical hydrogen compressor, PEMFC components, stacks, fuel cell forklifts and stationary power supplies, have been built and are already operational. Other prototypes, such as a fuel cell load haul dumper, are in the planning or initial construction phase. This approach of prototypes and demonstration units, referred to as strategic niche management, is critical to growing the credibility of a new technology within a well-established sector such as energy, as discussed previously.

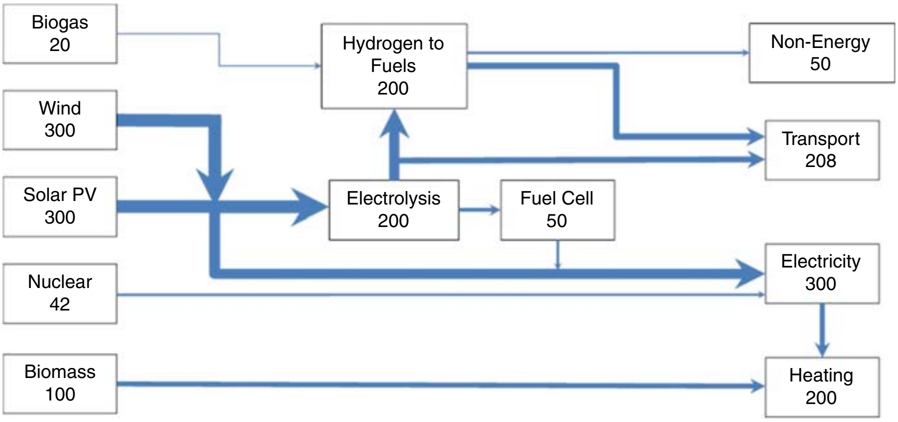


Figure 5. Sankey diagram for a decarbonised energy system in South Africa (TWh; 2014)

Commercial revenues within the sector are low, most of the resources are derived from public funds distributed by the Department of Science and Technology, and much of the activity is taking place at university-based research centres. Although some fuel cells have been installed, these are primarily demonstration facilities which are intended to explore niche applications within existing markets. Entrepreneurial activity, which is critical to the take-off phase, is located mostly around or within the research centres of HySA and outside of these networks there is little evidence of small firms engaged in product or service development.

Given the overall orientation of the fuel cell sector, namely, as a key technology to support decarbonisation and the enhancement or at least preservation of public goods, it is also evident that there is significant international collaboration and knowledge exchange within the local sector. Apart from the presence of international researchers within the research centres, drawn from a broad cross-section of countries, the study also revealed several cases of bilateral agreements with joint programmes in key areas of technology development. Although national programmes funded by public money tend to procure and work locally, in order to maximise any benefits as may be derived for domestic firms and industries, there are projects in which HySA has been able to link with international collaborations.

Table III also provides a useful summary of the key weaknesses within the fuel cell TIS. Although there are talks with a key investor (Chemours Company), these discussions are at an early stage and have not led to inward investment or technology transfer, both of which will be essential to the long-term sustainability of the TIS. Equally important is the observation that market formation remains weak with government not yet acting to develop or support local markets, as has been the case in South Korea (automobiles) and Japan (combined heat and power). On the positive side, it is noted that the aspect of "guidance of the search" has received attention with the publication of several roadmaps and innovation strategies, and the inclusion of fuel cells in departmental strategies. Further supportive steps in this regard, and particularly the implementation of strategy, will be important.

The issue of market formation links directly to the second focus of this study, namely, the concept of niche experimentation and how it can be deployed in order to stimulate the hydrogen TIS. There are several potential market applications for fuel cell technology which could be developed as market niches, including underground mining vehicles and inner city public transport, where in both cases air quality considerations limit the use of internal combustion engines, single-site electricity generation at chlor-alkali facilities, rural electrification and materials handling equipment, the latter including fork lift trucks (Industrial Development Corporation, 2016). Further discussion on these experiments and how they can be selected is presented in the next section.

5. Discussion

Applications of fuel cells are not competitive within the present socio-technical regimes and further progress in terms of the transformation of the energy generation/transport sectors, as required for 2DS, will not be possible without ongoing public funding and government support. However, South Africa (and other developing countries) cannot afford to establish experimental niches across the entire hydrogen value chain; the country will need to be highly selective and focussed in the allocation of its resources towards the enablement of the hydrogen economy.

In this regard, two important applications and one key intervention are now presented which could provide significant future opportunities for the country in addition to achieving the necessary changes in the transport and electricity sectors. It is noted that the selection of the two applications has been made on the basis of recommendations developed by Kim and Lee (2015) in their study of science and technology policy within middle-income countries, and particularly the differences between South-east Asia and Latin America. Their work

No.	Function	Status	Recommendations
F1	Entrepreneurial experimentation and production	Very limited entrepreneurial activity; commercialisation driven by university spin-offs and mining firms (platinum)	Increase efforts by public-funded commercialisation agencies to identify and support entrepreneurs within all components of the hydrogen value chain Establish fuel cell clusters within local science parks
F2	Knowledge development	R&D support focussed on the three Centres of Competence; limited firm-level R&D HySA has clear targets in respect of human resource and new product development	Increase public-funded product development in support of fuel cell components manufacture Develop fuel cell electric vehicles as a means of reducing pollution in underground and urban spaces Increase overall research effort including work presently being undertaken at universities and firms
F3	Knowledge exchange and diffusion	Engaging with international companies; talks at early stage only with the company Chemours Company, a Du Pont spin-off, for the local production of fuel cell components	Secure inward investments from international fuel cell companies resulting in foreign direct investment and technology transfer
F4	Guidance of the search	The National Hydrogen and Fuel Cell Technologies Research, Development and Innovation Strategy has been published by the Department of Science and Technology; similarly, the Department of Trade and Industry has included fuel cells in its policy documents	Drive new regulations based on COP21 commitments and safety requirements, including a carbon tax Implement more demonstration projects and improve legislative environment for distributed energy generation Include fuel cell power plants in the Integrated Resource Plan
F5	Market formation	Very limited activity; government has not acted significantly to develop local markets (the Department of Trade and Industry is considering a public transport project)	Implement more demand-side measures in support of underground mining, public transport, liquid fuels, rural electrification and materials handling
F6	Resource mobilisation	The main investor at this stage is the Department of Science and Technology Limited firm-level interest except for the platinum industry	Extend human resource development at the universities Expand public funding for fuel cell R&D/innovation/commercialisation
F7	Legitimation or counteracting resistance to change	Energy sector remains controlled by a powerful pro-nuclear and pro-coal lobby Some industry roadmaps in place (Impala Platinum and the Industrial Development Corporation)	Unlock barriers to distributed energy generation and heighten public awareness of the benefits of the hydrogen economy Introduce awareness raising programmes within primary and secondary education. Support a fuel cell industry association

Table III. Status of the functions for the hydrogen TIS

has suggested that it is important to select areas which have high capacity for the development of technological rather than scientific knowledge, and second that these areas should comprise of products or services with short-cycle times (Lee, 2016). The latter is especially important in the case of South Africa which has been struggling over a significant period with low economic growth and the classic symptoms of the middle-income trap (Seekings and Nattrass, 2015).

South Africa has already attempted to develop its own electric vehicle, unfortunately not with any success (Swart, 2015), with the main issue being the collapse of government funding and the absence of commercial partners/venture capital funding. It is important to learn from this experience and avoid its repetition with the hydrogen TIS. As a result, the two examples have been proposed on the basis of strong local markets/commercial interest (public transport) and short-cycle times (digital technologies for grid management). In general, software-based products or services, broadly referred to here are software technologies, are characterised by short-cycle times, rapid changes in markets and underlying technological competencies and open innovation, all of which are highly relevant to the present context in South Africa. The recommendation of grid-management software is moreover closely aligned with the capability being developed within the Square Kilometre Array (Dewdney *et al.*, 2009) and suggests that the country could apply a similar set of skills to the more widespread problem or application of integrating multiple energy sources within a national electricity grid.

5.1 *Niche experimentation in the transport sector*

Demand-side intervention as a means of changing the liquid fuels sector has a strong historical precedent in South Africa. In the 1950s, the government established Sasol as a local producer of liquid fuels based on the gasification of coal to produce syngas (a mixture of carbon monoxide and hydrogen) followed by the Fischer Tropsch process. The company has since expanded and continues to supply 30 per cent of the country's liquid fuel needs. However, the coal-to-fuel technology is highly polluting and the company's facility at Secunda is considered to be the single largest emitter of greenhouse gases in the world.

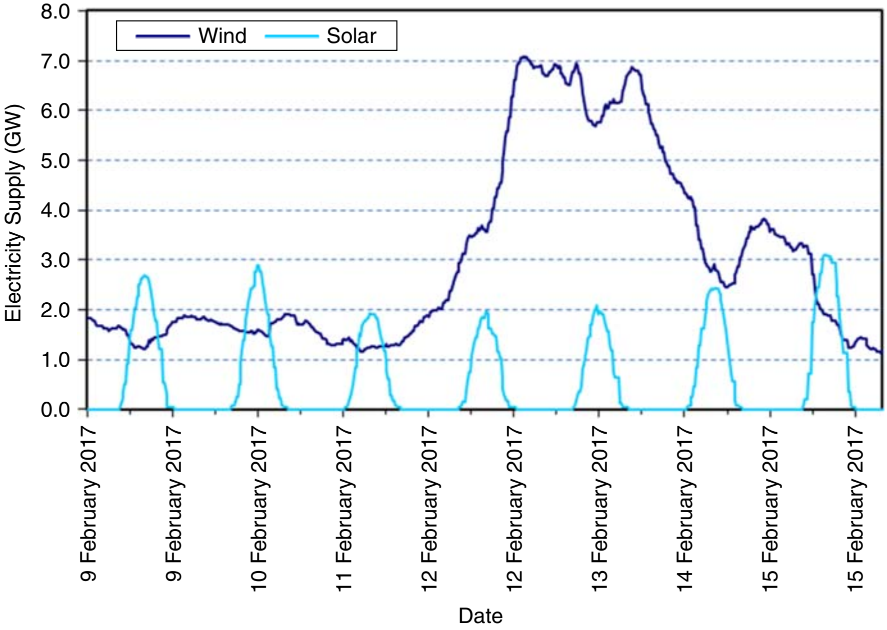
An alternative fuel system for the transport sector could be developed based on hydrogen. Although some of the industry analysts predict a strong growth in both battery and fuel cell electric vehicles (Sassams and Leaton, 2017), it is unlikely that this will happen based on the present cost and performance levels of the technology. In the initial (formative) phase niche experimentation, as outlined in the previous sector, will be essential. It is proposed that the use of fuel cells in the metropolitan public transport sector will be ideal in this respect. Buses operate on a round trip basis, which reduces the need for a distribution hydrogen infrastructure, and the present use of diesel in the inner city is considered to raise levels of dangerous particulates, as already mentioned.

5.2 *Digital technologies and grid management*

Although renewable technologies offer a viable alternative to energy generation in terms of costs and emissions, these technologies suffer from the intermittent nature of the resource. As a result, the transition to renewable energy has already presented, and will increasingly present, challenges for the stable management of national energy grids.

An example of the intermittent nature of wind and solar is shown in Figure 6, which presents the electricity generated in France from these two sources over the period 9 February to 15 February 2017. In many instances over this period the time constants for the fluctuations were too high for a compensating response from the base generators, particularly coal, lignite and nuclear. Although small changes happening over relatively long periods can be accommodated, this is not possible with large changes (>5 GW) in periods of less than 2–3 h. Such fluctuations have to be addressed by increasing the output of gas turbines, where additional capacity can be brought on stream relatively quickly, or by imports from neighbouring countries.

Digital technologies will be critical to the management of supply fluctuations induced from an increasing dependence on renewable resources. Although integration of relatively low levels of renewables has not yet presented major concerns, this will not be the case at higher levels of penetration (Chudy *et al.*, 2015), and the issue has already received widespread attention, becoming a subject of global research (Morales *et al.*, 2013). Apart from the sudden changes in supply factors, the integration of renewables into national grids has been described as a change from deterministic to stochastic production facilities,



Source: Gridwatch (France), available at www.gridwatch.templar.co.uk/france/

Figure 6. Intermittency of wind and solar electricity generation

reflecting the perspective that renewable resources change more extensively and the changes are more random (less predictable). Solutions to this problem include the introduction of capacitance or storage, the use of energy markets, better forecasting of demand and real-time control based on stochastic algorithms.

The use of digital technologies is clearly central to all of these approaches. In addition to real-time data about the performance of multiple sources of energy, there is a need to control demand and integrate energy pricing into consumer choices. More detailed study of these requirements within the South African energy should be the subject of future research.

5.3 Awareness raising and absorptive capacity

Legitimation, which refers broadly to addressing the social acceptability and desirability of a technology, and thereby counteracting any public resistance to transformation, is a highly necessary component of establishing a successful TIS, particularly where it could lead to a long-term sustainability transition (Andersson *et al.*, 2018; Edsand, 2017). Possible interventions addressing this aspect include both formal and informal lobbying, further details of which are now presented.

Formal lobbying includes the establishment of industry associations which actively promote the sector among the various stakeholder groups including government departments, research organisations, financiers and private companies, and where necessary, lobby for the introduction of regulatory or infrastructure systems to support the adoption of a new technology. Some recommendations in this regard have already been made in Table III.

Informal lobbying covers campaigns to raise public awareness of the technology and its potential benefits. Such campaigns can be introduced at various levels and by multiple actors, including government and industry associations. Examples of possible interventions include the development of learning materials for use in primary and secondary educational institutions, the raising of public awareness through targeted information campaigns and the establishment of public fora where research and environmental groups can engage in debate on the relevant issues, including the unforeseen on unintended consequences of a new technology.

There are several examples where public opposition has resulted in delays to, or even the termination of, technologies for sustainability transitions (Devine-Wright, 2007). It is therefore important that governments should understand the risks of a new technology and engage with the public in an open and participative manner on its possible adverse effects. In the case of hydrogen fuel cells, it is also important that government agencies and departments should implement educational and awareness campaigns at all levels, but particularly within secondary educational institutions, in order to allow the public to make an informed decision on the technology.

Such an initiative will also have the benefit of increasing the absorptive capacity for hydrogen fuel cell technology. The importance of the latter in successful technology transfer and diffusion is well understood (Bell and Pavitt, 1992; Cohen and Levinthal, 2000), and links to an earlier recommendation from Table III which stresses the importance of facilitating technology transfer from international fuel cell companies. Such transfer is unsuccessful when local absorptive capabilities are weak; a public awareness campaign at secondary school level will assist in generating enthusiasm for further human resource development in the fuel cell sector, and directly increasing the capability of the hydrogen TIS to adopt new technology.

6. Conclusions and recommendations

South Africa's energy system is well-suited to a sustainability transition which is based on high levels of wind and solar energy generation combined with a well-developed hydrogen economy, where the latter includes facilities for hydrogen generation via electrolysis, gas-to-liquids conversion and fuel cell electric transport. Many of these technologies are already in place and can be adapted to a more broad-based energy system which meets the targets of 2DS.

However, a review of the hydrogen economy in South Africa using the TIS framework has shown that it is still in a formative or pre-development phase and ongoing government support through funding of new product development. Niche experimentation is essential if the goals of the programme are to be realised. In particular, the application of PEMFC in public transport as a replacement to diesel-based buses in the metropolitan areas, and the development of digital technologies for the integration of various sources of energy (wind, solar, coal, nuclear, gas and fuel cell) are proposed as areas of more intense research. Although in many applications digital technologies can be considered as providing an opportunity, in this case the use of such technologies will be essential; indeed, it seems unlikely that the transformation of the energy sector will be possible without the use of digital technologies that will allow real-time control of what are in reality highly stochastic systems. This proposal as an area of focus for niche experimentation also aligns with recent policy recommendations of developing short-cycle products and focussing on technological rather than scientific knowledge (Lee, 2016).

In many respects, South Africa presents a less intractable energy transformation challenge since it has high-quality renewable resources and a more limited dependency on oil. However, as described in this paper, the cost barriers of hydrogen fuel cells make such a transition uneconomic in the short term and ongoing experimentation is required to achieve this goal. It is recommended that niche applications are supported in the key areas of public transport, and digital systems to facilitate the integration of dispatchable and non-dispatchable sources of energy. Other recommendations include establishing science parks to support the local manufacture of fuel cells and fuel cell components, stimulating foreign direct investment from international fuel cell companies as a means of increasing technology transfer, and introducing regulatory or policy measures to favour the application of hydrogen fuel cells within the transport and energy sectors.

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