An Analysis of Fuel Cell Technology for Sustainable Transport in Asia

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Abstract

Purpose: Fuel cell technology is often discussed as a potential alternative to existing vehicle power systems such as petrol or diesel combustion engines due to the higher potential thermodynamic efficiencies, and low or even zero, direct greenhouse gas emissions. However, despite intensive public and private research efforts into developing fuel cell vehicles (FCV), particularly in Japan, the U.S.A., and Canada, the global number of vehicles is still less than 1000. A number of barriers to commercialisation have been identified previously, including the high cost of components such as the electrocatalyst and the membrane, difficulties in onboard hydrogen storage, and the development of supporting fuelling infrastructure. This paper aims to describe the current status of this technology and the policy measures being adopted in various Asian countries to support its development.

Methods: Research activity and current technical status in three key Asian countries (Japan, S. Korea, and P. R. China) is examined using in-depth literature review, bibliometric and patent analysis. This data is then analyzed through the conceptual framework of Rogers' innovation diffusion curves.

Results and Discussion: The data shows that whilst Japan, which has had a long-running fuel cell program, continues to be the leading innovator in FCV, China and Korea have made remarkable progress in the last 15 years. The organisation of the fuel cell programs differs substantially between the countries and reflects different priorities and institutional arrangements. The university sector is responsible for a significant proportion (49%) of patents from China whilst Japanese patent filings are dominated by a variety of private companies. Marked increases in activity are noted, suggesting progress along the innovation 'S-curve'. Despite this substantial activity, the absence of any mass-production FCV and the current economic uncertainty makes it unclear whether a breakthrough in FCV will be achieved.

Introduction

The demand for security of supply, the need to tackle air pollution and climate change, resource constraints, and the opportunity to promote new industries from innovation in the energy sector are prompting changes in the energy sector (OECD, 2006). Whilst in the short to medium term, it is likely that the majority of global energy demand will continue to be met by the combustion of fossil fuels particularly oil and gas (EIA, 2011), it is less obvious how countries will fulfil the need for clean and dependable energy beyond 2050. Although there are grounds for optimism for a transition to occur in the stationary power sector through greater use of alternative technologies such as solar, wind, geothermal, hydro, and, more controversially, nuclear power and carbon capture and storage (Kannan, 2009), it is more difficult to address the problem in the transport sector. This is because easily substitutable options for the energy dense gasoline and diesel fuels currently used, are not readily available or economic.

Transport as a whole, accounts for 27% of global energy demand, of which almost all is derived from fossil fuels, particularly gasoline (IEA, 2010). The gross contribution of transport to global CO_2 emissions is expected to rise, partly driven by the economic development of nations such as India and China. For road transport, Dargay and Gately (1999) have shown that increases in income, particularly when starting from a low base, correspond to a large increase in car ownership. Whilst the population of vehicles is expected to saturate in the rich-world countries of the Organisation for Economic Co-operation and Development (OECD), substantial growth is expected across the non-OECD countries (Dargay and Gately, 1999). Although some success has been found in decoupling economic growth from road freight (Sorrell et al., in press), the effects have been modest, and it is unlikely to be a viable strategy for tackling light-duty vehicle (cars and small trucks) emissions. There is also of course, the social equity issue of trying to restrict citizens from emerging nations from having access to lifestyles possessed by generations of rich-world nations. One of the challenges is thus to develop affordable technology options which can provide the convenience of existing automobile performance but without the reliance on fossil fuels.

This paper will examine the status of one such possible alternative, hydrogen fuel cell vehicles, particularly within the context of three key Asian countries: Japan, the Republic of Korea (S. Korea), and the People's Republic of China (China). These countries were chosen due to the size of their respective car markets, and the presence of major car manufacturers. First, an overview of the technology is given. Second, a perspective on the R&D programmes of the three countries is presented. Finally, using patent and bibliometric analysis, a novel assessment of the scale and efficacy of these national programmes is put forward.

Current Status of Technology

Fuel cell vehicles (FCV) work in a fundamentally different way to traditional combustion engine vehicles. Rather than using the controlled explosion of petroleum-derived fuel to drive pistons up and down to produce motion, a fuel cell converts the chemical energy stored in the fuel directly into electrical energy without the intermediate step of transferring heat to-and-from a working fluid (Lutz et al., 2002). This process is more efficient than the combustion engine as less energy is lost as waste heat, light, and sound. However, comparisons of efficiency can vary dramatically depending on where the system boundary is drawn, e.g. well-to-wheel or tank-to-wheel (MacLean and Lave, 2003). When hydrogen is used as the fuel for the cell then the reaction produces only water as the tailpipe emission, as shown by the following equations:

$$H_2 \rightarrow H^+ + e^- \quad \text{(hydrogen oxidation)} \quad [1]$$

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad \text{(oxygen reduction)} \quad [2]$$

$$1/2O_2 + H_2 \rightarrow H_2O \quad \text{(overall reaction)} \quad [3]$$

This is in contrast to the harmful CO, CO_2, NO_x, SO_x and particulates that are emitted from fossil fuel combustion (MacLean and Lave, 2003). However, unlike fossil fuels which can be found naturally occurring in various deposits around the world, hydrogen must be derived from a primary energy source. Currently, the majority of the world's hydrogen is produced from the steam reformation of natural gas, which results in the simultaneous co-production of CO_2 (Bauen and Hart, 2000). Thus, a criticism of hydrogen fuel cells is that they simply shift the emissions problem from the tailpipe to the reformation plant, with an associated loss of efficiency as well. However, many other options to produce H_2 from renewable, non-fossil sources are being investigated (Kleijn and van der Voet, 2010). The broader issues of the supporting hydrogen production and infrastructure needed to support FCV are not considered here though but a useful overview is given by Schlapbach and Zuttel (2001).

A range of different designs are available and are grouped according to the electrolyte employed. Polymer electrolyte membrane fuel cells (PEMFC) are particularly well-suited for use in vehicles due to their relatively low operating temperature which gives quick start-up times and quick response to load changes (Barbir and Gomez, 1996). The other main types such as solid oxide, alkaline, phosphoric acid, and molten carbonate are in various stages of development with solid oxide fuel cells already gaining some high-profile deployment through Bloom Energy in the USA (Bullis, 2010). The underlying principle is the same for all of the different designs, although the materials challenges involved differ significantly.

Despite the relative simplicity of the PEMFC, there are a number of technical challenges that must be overcome in order to make the vehicles cost-competitive with existing combustion engine vehicles, and satisfactory to consumers in terms of performance. It is difficult to make a direct price comparison between an FCV and a traditional vehicle as there are no FCV currently available for purchase and there is commercial sensitivity surrounding production costs for prototype vehicles. Unfortunately this leaves considerable speculation about both current costs and the potential cost reductions available from mass production – one 2004 estimate gave the price per unit power for a PEMFC as \$3000/kW versus \$30/kW for a gasoline engine (Crabtree et al., 2004). A typical vehicle requires between 50 - 80 kW (Schoots et al., 2010). A major reason for the high cost of the PEMFC is that it requires expensive, and scarce, platinum to be used as the electrocatalyst at both the anode and cathode. This accounts for about 77 % of the stack cost (Carlson et al., 2005). The electrocatalyst is an essential component that increases the rate of reaction in order to produce sufficient current to drive the vehicle comfortably. Two strategies to overcome the high cost of the electrocatalyst are currently being pursued: in the short-term, development of ultra-low Pt loading techniques (Martin et al., 2010); and in the longer-term, development of Pt-free alternative materials (Haslam et al., 2011). Other materials challenges such as the membrane are detailed in (Steele and Heinzel, 2001).

Finally, it is also useful to consider the other alternative technology options, in addition to FCVs, that are currently being developed, their stage of development and their relative strengths and weaknesses. This information is summarised in Table 1. The possible options include hybrid electrics such as the Toyota Prius, plug-in hybrids such as the Chevrolet Volt, 'full' or battery electrics such as the Nissan Leaf, and the FCV. It may of course be possible that the future vehicle sector contains a greater diversity of power-trains rather than being dominated by a single technology. (Yarime et al., 2008) have shown that the development of new vehicle technology is sensitive to changes in legislation and policy with changes in the car manufacturer Toyota's patent activity closely corresponding to changes in the State of California's zero-emission vehicle (ZEV) legislation. However, this is a dynamic process between manufacturers, policymakers, and other stakeholders. For example, the electric vehicle, which was discontinued in favour of the FCV in the 1990s due to concerns about range (Dijk and Yarime, 2010), is now launching as a commercial vehicle whilst FCVs are still stuck in the prototype stage. The various efforts to promote the research and commercialisation of FCV in Japan, Korea, and China, are outlined in the next section.

Table 1. A comparison of the current and possible alternative vehicle power-trains available.

Technology	**Development**	**Strengths**	**Weaknesses**
Internal combustion engine (ICE)	Currently dominates road transport sector. Continuous improvements in fuel efficiency.	• Economic • Long life • Established supdporting infrastructure • Consumer acceptance	• Air pollution • CO_2 emissions
Hybrid electric vehicle (HEV)	Introduced commercially by Toyota 1997. Cumulative sales of 1 million vehicles by 2010	• More fuel efficient than ICE • Uses existing fuel infrastructure • Developing consumer acceptance	• Still relies on petrol fuel • Relies on subsidy to compete with ICE
Plug-in hybrid-electric vehicle (PHEV)	First commercial vehicles launched by BYD (China) and Chevrolet (USA) in 2010.	Same as HEV but: • Zero emissions in all-electric mode • No range anxiety • Flexible power	Same as HEV but: • Requires charging infrastructure • Battery stability
Battery electric vehicle (BEV)	Range of commercial vehicles available from Nissan, Renault, and Mistubishi and others since 2010.	• Zero emissions	Same as PHEV but: • Range anxiety
Biofuel ICE	Many countries around the world mandate between 2 – 10% blend of bioethanol or biodiesel with regular fuel	• Possible reduction in overall CO_2 • No new fuel infrastructure • Uses existing ICE	• Subsidy required • Environmental degradation • Competition with food crops
Hydrogen fuel cell vehicle (FCV)	Numerous prototype vehicles and pilot programs but no commercial vehicles	• Zero tailpipe emissions • No range anxiety • Greater conversion efficiency than ICE	• Major infrastructure needed • Currently rely on methane for H_2 fuel • Very expensive

The Situation in Japan

Due to its relative lack of natural resources in terms of energy, and the strategic economic priority placed on developing new technologies, as evidenced by the comparatively high proportion of GDP spent on R&D, Japan has been at the forefront of fuel cell research for the past thirty years (IEA, 2008). Development of fuel cells was initiated with the *Moonlight Program* in 1981 which led to the successful deployment, and eventual commercialisation, of large-scale (1 MW) phosphoric acid fuel cell (PAFC) for use in stationary power generation (Anahara et al., 1993). PEMFC, which only started to appear as an option for vehicles in 1992, were investigated largely independently of government support by Japanese carmakers such as Toyota between 1992 - 2000 (Ishitani and Baba, 2008). However, the announcement in 1997 by Daimler-Benz of its ultimately failed ambition to commercialise FCV by 2004, led to the development of a strategic plan involving the Japanese Ministry of Economy, Trade, and Industry (METI), and selected Japanese firms to co-operate on developing PEMFC and FCV (Harayama et al., 2009). The result of this was the launch of a highly co-ordinated three-phase program between METI and a number of Japanese companies called the Japan Hydrogen and Fuel Cell (JHFC) project. It was intended to provide for the full-scale deployment of hydrogen FCV and the associated H_2 production, storage, and filling infrastructure (Ishitani and Baba, 2008). The high level of co-ordination between industry and government, along with specific technology promotion reflects the higher degree of state-corporatist planning prevalent in Japan, than for example, the USA (Vasudeva, 2009).

The first phase of the JHFC ran between 2002 – 2005 and aimed to develop the H_2 infrastructure and to determine performance statistics from a small fleet of FCV, with MEXT providing ¥ 2 billion / yr over the trial period (Kamimoto, 2005). A second phase ran from 2006 – 2010 and aimed to develop codes and standards, reduce costs, and identify technology and policy trends in FCV and hydrogen infrastructure. This phase had an annual subsidy of ¥ 1.3 billion / yr (Tomoru, 2010). However, there is uncertainty as to whether the third phase which aimed to begin market demonstration of FCV will now proceed or whether a new program will replace it (Tomoru, 2010). Despite this, a statement signed in 2011 commits an alliance of carmakers and hydrogen suppliers, including Toyota, Nissan, and Honda, to releasing commercial fuel cell vehicles by 2015 (METI, 2011). Whether this will ambition will be realised is not known.

The Situation in Korea

Similar to Japan, Korea is particularly reliant on foreign oil imports and imports 97% of its primary energy (Kim and Moon, 2008). This sensitivity to changes in oil price and vulnerability to disruptions in supply, as well as other concerns over the environment, have prompted the development of a significant hydrogen fuel cell program (Kim and Moon, 2008). Following the enactment of the Alternative Energy Promotion Act in 1988, the Hydrogen and Fuel Cell R&D program was initiated (Lee, 2008). Between 1988–2003, a total of US$ 91.5 million was invested through a combination of public and private sector contributions. A change of policy in 2003 led to a substantial change in fuel cell R&D when the Government identified fuel cells as a key technology in the 10-year Basic Plan for the Development and Dissemination of New and Renewable Technology (OECD, 2006). Since 2003, the size of this investment has been increasing year-on-year, with US$ 110.8 million invested in 2007 alone (Lee, 2008). The current funding program will end in 2012 and new budgets and priorities will then have to be set.

Technical expertise in the fuel cell technology sector is spread across a range of public and private sector organisations, although government funding exceeds that estimated from industry (OECD, 2006). The main responsibility for allocation of funding and promoting public-private collaboration is handled by the Ministry of Knowledge Economy (MKE) and the Ministry of Education, Science and Technology (MEST). MKE tends to focus on short-term practical fuel cell applications whilst MEST leads the development of basic research (Lee, 2008). There are a range of research institutes and universities which are involved in achieving the research objectives outlined in the Basic Plan, with the Korean Institute of Energy Research (KIER) being one of the most prominent (Lee et al., 2009).

Korea is also the 5th largest vehicle producer in the world and with Hyundai-Kia, it has one of the world's largest car makers (OICA, 2010). Hyundai-Kia has an active fuel cell vehicle program and is working with the MKE to accelerate commercialisation. In 2008, it was announced that Hyundai-Kia would produce 3,200 FCV cars by 2012 (Lee, 2008), although this has since been revised down to 500 cars (Rechtin, 2010).

The Situation in China

Car ownership has been rapidly increasing in China, and in 2010 it became the world's largest automobile market and manufacturer (OICA, 2010). This increasing volume of vehicles, as seen in Fig. 1., has spurred efforts to tackle the associated problems of air pollution, climate change, and foreign oil dependence (Hu et al., 2010).

The Chinese Government has identified alternative vehicles, including FCV, as a key strategic priority and aims to leapfrog the existing technology leaders in the US, EU, and Japan (Hu et al., 2010). Various prototype stacks and vehicles have been developed since the 1950s although Qian et al. (2003) are critical of the previous lack of coherent direction in the Chinese fuel cell program and the limited ability to commercialize the fruits of that research. However, fuel cell vehicles (both passenger cars and buses) are now the recipient of significant research funding from two different programs – the High Technology Development Program (commonly referred to as the 863 Program), and the National Basic Research Program (also called the 973 Program) (Zheng et al., 2012).

Research and commercialisation priorities are set out in 5-year planning cycles and in the most recent plan (12th Five-Year Guideline), which covers the period 2011-2015, a goal of delivering 500,000 alternative vehicles on the road was set (Hannon et al., 2011). Significant amounts of money will be invested, with RMB 50 billion yuan (US $7.6 billion) allocated for R&D and industrialisation (Hannon et al., 2011). It should be noted though that these figures are the combined totals for all alternative vehicle projects, including BEV, PHEV, and FCV, and do not provide an accurate account of the specific activity in the FCV sector. However, more specific previous figures for combined hydrogen and FCV R&D have been estimated at $20 million per year (2001-2005) (Hu et al., 2010), and RMB 75 million per year (2006-2010) (Tan and Gang, 2009).

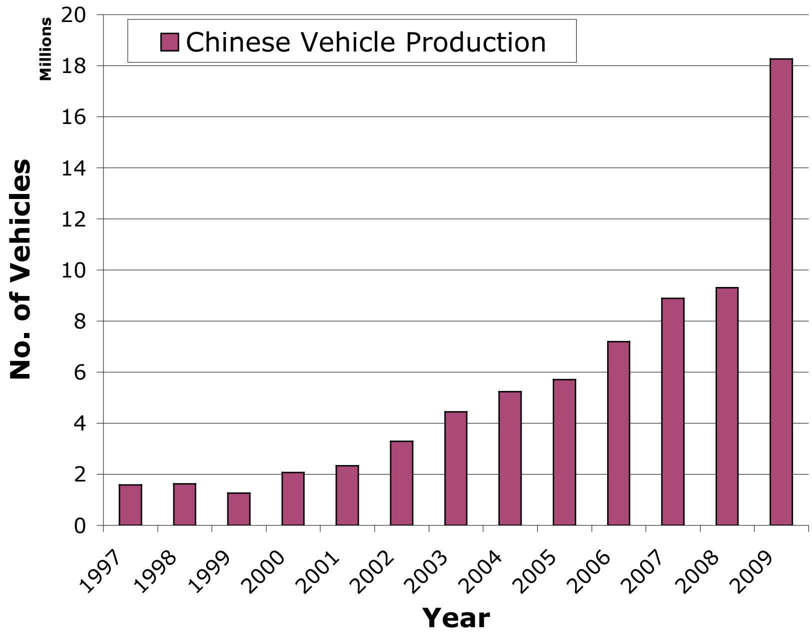

Fig. 2. Growth in Chinese vehicle production over time. Source: OICA (various years).

Methodology

Technology development and innovation diffusion has often been found to follow an 'S-curve' characterised by slow initial progress, followed by rapid advancement, and finally reaching a plateau indicating market dominance, as first described by (Rogers, 1995). Trying to accelerate a particular technology or portfolio of technologies progress up the S-curve is often the subject of policy initiatives, although with mixed results (Stoneman and Diederen, 1994). The use of patent and journal publication data is one method that can help identify trends in technology development and assist policymaking. The following assesses the respective data in relation to Japan, Korea, and China.

This work makes use of two different datasets in order to assess different aspects of the development of fuel cell vehicle technology. The first source of information is the Science Citation Index Expanded (SCIE) database, a product from Thomson Scientific. This database, which is accessed through the Web of Knowledge™ internet portal, provides one of the largest collections of easily searchable science and technology journal abstracts, as well as citation reports on the published literature. The number of citations of an article or journal by academic peers can be used as a metric to weigh the relative importance or impact of the respective article or journal. Such data can also be useful in describing various trends in a scientific field such as the rate of progress, the geographic spread of research, and the intensity of collaboration (Meyer and Persson, 1998). The keyword search term used in this paper was "hydrogen fuel cell". The search was conducted so that any records which contained all three words in any combination in either the title or abstract were returned in the results. This was deemed to be the most effective search to return results closely linked to the development of technology related to FCV whilst attempting to exclude the substantial literature related to hydrogen production and storage. The search period covered the years 1965 to 2010.

The second source of data was the esp@cenet® patent database which can be accessed for free through the European Patent Office website. The database is particularly useful in that it allows the user to search simultaneously patents filed at more than 80 national patent offices, including the United States, Japan, Korea, and China. It can therefore be considered to give a comprehensive coverage of patent information. Whilst organisations such as the OECD publish general statistics on the number of patents filed in particular technology sectors such as photovoltaics or hydrogen and fuel cells, the OECD database does not usually provide information on non-OECD countries or allow fine-tuning of the search terms. Patents are a useful, if imperfect, measure of innovation in that they represent a novel process or artefact which includes a non-obvious inventive step that has commercial viability (Dernis and Khan, 2004). A key criticism of patent analysis is that the existence of a patent does not necessarily lead to the eventual release of a successful product (Johnstone et al., 2010). However, it remains a useful quantifiable measure of the success of policy in encouraging innovation, and as Dernis and Kahn (2004) point out, there are few economically significant inventions that have not been patented. One remaining, unresolved criticism is that there is an English language bias in both the journal and patent database analyses.

The patent search was conducted using the search term "fuel cell NOT biofuel". This returned all patents which contained the term "fuel cell" in either the title or abstract. The use of "NOT" excluded any references to "biofuel". Due to the slightly more vague wording sometimes used in patent filings it was decided to include the broadest range of data by using "fuel cell" rather than "hydrogen fuel cell". This had a positive effect in that many patents relating to solid electrolyte fuel cells were returned but also meant that many non-vehicular patents such as those relating to molten carbonate and solid oxide fuel cells were included. However, their inclusion was accepted on the basis that it relates to the general development of the field and improvements in one area may have benefits for other fields. Cumulative world data was collected over the period 1960 – 2009 whilst country specific data was collected over the period 1994 – 2009. Prior to 1994 both China and Korea have essentially zero fuel cell patents.

Results and Discussion

The growth in interest in fuel cell technology over time is shown in Fig. 2. The solid line shows the number of patents granted between 1960 and 2009 as recorded in the esp@cenet database using the search-term "fuel cell NOT biofuel". This data includes patents related not to just hydrogen fuel cells (which are most closely related to FCV) but also to molten carbonate and solid oxide fuel cells (MCFC and SOFC). The number of articles containing the term "hydrogen fuel cell" published in scientific journals as indexed in the SCIE is shown by the dashed line in Fig. 2. The two trends have been plotted on different vertical axes to make it easier to distinguish changes over time. The dates of key policy measures have also been indicated.

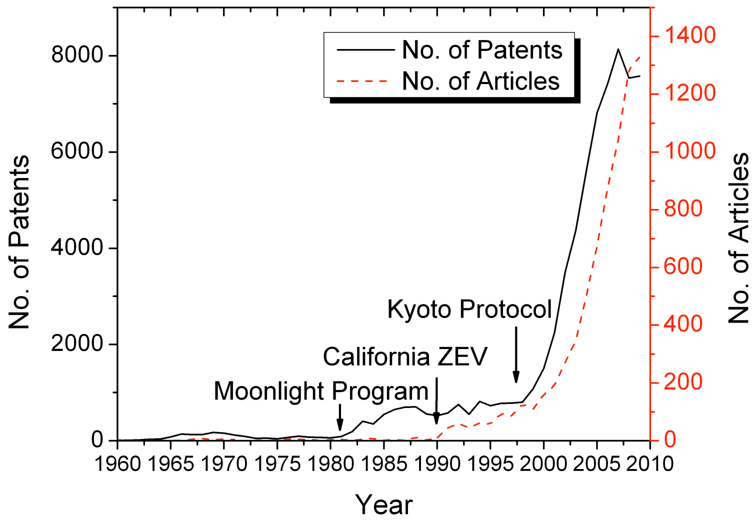

Fig. 2. The growth in worldwide fuel cell activity as shown by a keyword search of the esp@cenet patent database (solid line) and the SCIE citation database (dashed line). Note the change in vertical scale between patents and articles. Key policy developments are noted on the graph.

It is possible to distinguish a number of key features in the general field of fuel cell technology from Fig. 2. The form of both the patent and publications trends seems to follow the S-curve typical of technological innovation as described by Rogers (1995). Between 1960 and 1980 both curves remain relatively flat, apart from a small 'hump' between 1965 and 1972 that relates to patenting of the discoveries arising from the US space program (as shown by the large number of patents filed by United Aircraft – a NASA contractor). A more significant increase in fuel cell patenting activity starts in 1981, which corresponds with the launch of the Japanese *Moonlight Program*. Much of this activity is not directly associated with FCV but rather it describes the efforts to develop high temperature fuel cells such as phosphoric acid FC and MCFC for home power generation. Of the 4,241 fuel cell patents published between 1981 and 1989, 18% contain either PAFC or MCFC in their title or abstract. It is not until 1990 that significant activity in vehicle-related fuel cells (PEMFC) starts to occur as shown by the upturn in the dashed-line that indicates the number of academic publications on hydrogen fuel cells. This coincides with the introduction of the zero-emission vehicle (ZEV) legislation in California, as well as a range of technical breakthroughs such as the development of high performance solid electrolytes and low Pt-loading electrodes (Perry and Fuller, 2002). Finally, it is seen that there is a sharp rise in patent and publication activity after 1997. This coincides with the adoption of the Kyoto Protocol of United Nations Framework Convention on Climate Change which provided many incentives for the development of low-carbon technologies (Hepburn, 2007).

The development of fuel cell technology as specifically related to Japan, Korea, and China for the period 1995 – 2009, is shown in Fig. 3. The search terms and data sources are the same as in Fig. 2. with patent data shown by solid lines, and journal data shown by dashed lines. Again, there is a change of vertical scale between the two datasets. Prior to 1995, neither Korea nor China had any significant fuel cell research outputs, at least as reported in the esp@ace.net and SCIE databases. Japan on the other hand had filed many patents prior to 1995 from a wide range of companies including Toshiba, Hitachi, Fuji Electric, Toyota, Honda, Nissan, Nippon Telegraph & Telephone, Osaka Gas, Tokyo Gas, Mitsubishi Electric, and Tanaka Precious Metal. This pre-existing industrial base has grown rapidly since 1997 as shown by the increase in patents originating in Japan in Fig. 3, giving it a significant lead over both Korea and China. However, in terms of the number of academic hydrogen fuel cell publications (shown in Table 2), Japan has been overtaken by China. It appears then that in the relatively short time since the introduction of the 10 Year Basic Plan in 2003 in Korea and the 10th Five-Year Plan in 2001 in China that provided the policy support for fuel cell R&D in those countries, that they have been successful in gaining ground on the established leader, Japan. It is noted though that the growth in Chinese patent activity is quite small.

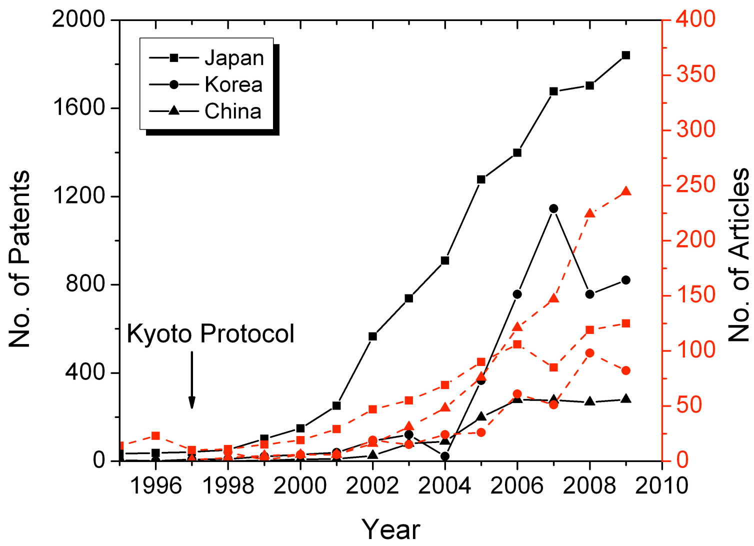

Fig. 3. The growth in hydrogen fuel cell activity in Japan, Korea, and China as indicated by keyword searching of the esp@cenet and SCIE databases. The patent search-term was "fuel cell NOT biofuel" (solid lines) and the citation search-term was "hydrogen fuel cell" (dashed lines). Note the change in *y*-axis.

Table 2. The number of journal articles published in each year from Japan, Korea, and China, along with the total number of publications using "hydrogen fuel cell".

	'95	**'96**	**'97**	**'98**	**'99**	**'00**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**'08**	**'09**
China	0	0	1	3	5	6	6	16	31	48	76	121	147	224	244
Japan	14	23	10	11	15	19	29	47	55	69	90	106	85	119	125
Korea	0	0	0	8	1	6	6	19	15	24	26	61	51	98	82
Total	57	96	85	128	110	160	190	271	345	502	675	875	1043	1285	1328

The location and concentration of academic activity in each of the three countries can be seen in Table 3. The table shows that in each of the three countries the most productive institution is a national research institute which was specifically identified as a key focus for fuel cell research by the relevant policy document. The quality of publications, rather than simply the quantity of publications, can be judged by the number of citations. The average number of citations for each fuel cell article published between 1995-2009 was 20.82 for Japan, 19.24 for Korea, and 14.42 for China, as determined from the SCIE database. This suggests that whilst Chinese researchers are more prolific than their colleagues in Japan and Korea, the relative influence of the research may be lower.

Table 3. The most productive institutions in each country in terms of publication amount for the period 1995-2009.

Country	**Institution**	**Record Count**	**% of Country Total**
China	Chinese Acad. Sci.	232	25.0
	Univ. Sci. Technology	73	7.9
	Harbin Inst. Technol.	54	5.8
	Tsing Hua Univ.	48	5.1
	Shanghai Jiao Tong Univ.	44	4.7
	Tianjin Univ.	42	4.5
	Zhejiang Univ.	41	4.4
	S. China Univ. Technol.	31	3.3
	Sun Yat Sen Univ.	25	2.7
	Tongji Univ.	25	2.7
Japan	Inst. Adv. Ind. Sci. Technol. (AIST)	100	12.2
	Kyoto Univ.	58	7.1
	Tokyo Inst. Technol.	55	6.7

	Kyushu Univ.	52	6.4
	Tohoku Univ.	48	5.9
	Univ. Tokyo	48	5.9
	Nagoya Univ.	34	4.2
	Hokkaido Univ.	23	2.8
	Kogakuin Univ.	19	2.3
	Univ. Tsukuba	18	2.2
Korea	Korea Adv. Inst. Sci. Technol.	53	13.4
	Korea Inst. Energy Res. (KIER)	43	10.8
	Korea Inst. Sci. Technology	40	10.1
	Seoul Natl. Univ.	40	10.1
	Korea Univ.	32	8.1
	Yonsei Univ.	26	6.5
	Korea Res. Inst. Chem. Technol.	22	5.5
	Ajou Univ.	21	5.3
	Hanyang Univ.	20	5.0
	Samsung Adv. Inst. Technol.	18	4.5

Analysis of the institution of origin on patent applications reveals some distinct differences between the innovation strategies of the three countries. Within China, a significant fraction of fuel cell patents are filed by universities rather than private companies. In 2009 for example, of 275 patents filed by Chinese inventors, 49% named a university as the applicant. Many of the named universities are the same as those listed in Table 2. In Japan and Korea, patent filing was dominated by private companies, along with some patenting by research institutions such as AIST in Japan or KIER in Korea.

Both the bibliometric and patent data presented here in Fig. 2 show that there continues to be significant interest in the development of fuel cell technology. Currently, it seems that both industrial and academic research activity are following similar trajectories. In terms of the classical innovation theory promoted by Rogers (1995) and Utterback and Abernathy (1975), it might be expected to see a decline in academic publications prior to an upturn in patent activity as the technology moves from the research stage to the prototype and then full-scale commercialisation. The failure of previous prototype vehicles and the continued basic and applied research suggests that there are still a number of technical barriers preventing FCV from successfully competing in the marketplace. No attempt has been made to estimate to forecast if or when a breakthrough is likely to occur. Further study taking account of a greater range of variables such as cumulative investment and performance improvement (e.g. efficiency) combined with greater stratification of the data could be useful in highlighting the major bottlenecks and likely progress.

A second point relates to the effect of particular policy measures in stimulating innovation in the fuel cell sector. The coincidental relation between increases in either patent or publication activity and initiatives such as the zero emissions vehicle legislation or the Kyoto Protocol needs to be established further. However, Johnstone et al. (2010) have found a similar correlation across a range of renewable technologies using a slightly different methodology. Although, as Schilling and Esmundo (2009) point out, many countries such as the US and Japan still invest more in fossil fuel technologies than for renewables.

From the perspective of the new entrants into FCV research it is remarkable how quickly China and Korea have managed to gain ground with Japan, which has been an established world leader in various types of fuel cell research as well as vehicle manufacture. From the data provided, it is suggested that the various 5-Year and 10-Year Plans have been successful in stimulating public and private research in the area of hydrogen fuel cells. It may also be expected that given the relative population size of China, its share of publications, patents, and industrial activity will soon eclipse that of Japan. However, the fact that growth in Chinese patent activity is quite low and of the patents that are filed, 49% are from universities, indicates that the more command-and-control policy adopted in China is not creating enough private sector development in FCV.

As regards the ultimate question of how likely it is that a mass production FCV will emerge in the near future, it is difficult to conclude anything definitive from the results presented here. Each of the national ministries have demonstrated their commitment to trying to encourage a range of alternative vehicle technologies with a view to the eventual commercialisation of FCV preceded by hybrids and battery vehicles. Similarly, auto manufacturers in all three countries have made public statements concerning their plans to commercialise FCV within the next 5 years and continue to invest in fuel cell programs. Whether the sharp rises in activity observed here mean that the technical problems really have been overcome and that hydrogen fuel cell technology is progressing along the innovation S-curve remains to be seen.

The background to all this is the continued global uncertainty both in terms of the financial crisis and the successor framework to the Kyoto Protocol on Climate Change, which is due to end in 2012. For both academic researchers and industry, the Kyoto Protocol provided a degree of certainty that encouraged the planning and development of low-carbon technology. If the current uncertainty persists, combined with decreases in available funding, then much of the drive to develop FCV may be lost.

Conclusion

A range of technology options are being aggressively developed in order to make the transition to a more sustainable transport system. Whilst intermediate technologies such as hybrid electric and battery electric vehicles are beginning to penetrate the global market, the long-term goal of many government policies and companies is to commercialise hydrogen fuel cell technology. However, despite the considerable financial investment, research expertise, and business development, FCV remain unavailable for consumer purchase. The bibliometric and patent data presented herein shows that since at least 1997 there has been significant interest and development in this technology. Through innovation diffusion analysis, it is suggested that FCV may be making the transition from innovation/niche technology to commercialisation – in line with public announcements by manufacturers. Within the context of the countries studied here (Japan, China, and Korea), it is clear that Japan remains at the forefront of fuel cell technology both in terms of patent activity and academic research (by citations, if not simply by volume). The data shows though that China and Korea have been successful in catching-up to the more well-established programs in Japan. The concentration of publications within national research centres/academies indicates the success of the targeted policy approach. Although the relatively unsophisticated methodological approach used here gives an indication of general trends in technology, the question of whether FCV are ultimately constrained by technical limitations or the lack of appropriate supporting policy remains unanswered. Providing solutions to this problem would have important implications for improving the progress rate and encouraging innovation of many other emerging sustainable technologies.

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