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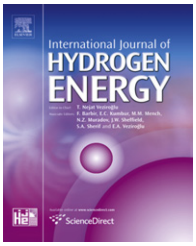

Assessing fuel cell vehicle innovation and the role of policy in Japan, Korea, and China

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ABSTRACT

Despite intensive public and private research efforts into developing fuel cell vehicles (FCV), the global number of FCV remains small and they are unavailable for commercial purchase. We use an in-depth literature review, and bibliometric and patent analysis to analyse FCV technology within the conceptual framework of Rogers' innovation diffusion curve and suggest how the particular innovation systems and policies adopted in three key Asian car-manufacturing countries (Japan, Korea, and China) have influenced the development of FCV. Such analysis may capture trends not indicated by technical measures such as increases in efficiency or decreases in unit cost. Although Japan continues to lead in terms of number of patents and quality of academic research, Korea and China have been successful in developing fuel cell programs. Korean academics patent more frequently than their Japanese and Chinese peers, producing 18% of FC patents, with 16% of those filed also naming a private company. The 2008 financial crisis and ongoing economic uncertainty appears to have had some effect on patent activity whilst academic research appears unaffected. Diffusion curve analysis suggests that FCVs have not reached technological maturity.

1. Introduction

The demand for security of supply, the need to tackle air pollution and climate change, resource constraints, and the opportunity to promote new innovation-led industries in transportation are prompting changes in the energy sector [1]. 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 [2], 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 [3], 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 economically viable.

Transport as a whole, accounts for 27% of global energy demand, of which almost all is derived from fossil fuels, particularly gasoline [4]. 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 [5] have shown that increases in income, particularly when starting from a low

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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 [5]. Although some success has been found in decoupling economic growth from road freight [6], 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 the issue of social equity, the rights of citizens of emerging nations to have the same lifestyle choices as of generations of rich-world citizens. One of the challenges is thus to develop affordable technology options that 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 in 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, the presence of major car manufacturers, and the different stages of economic development they represent. First, we present an overview of the technology. Second, a perspective on the R&D programmes of the three countries is presented. Third, using patent and bibliometric analysis, we put forward a novel assessment of the scale and efficacy of these national programmes. Finally, we make some policy proposals which we hope can stimulate innovation in this area.

1.1. *Current status of the 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 [7]. 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 [8]. 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:

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

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

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

This is in contrast to the harmful CO, CO_2, NO_x, SO_x and particulates that are emitted from fossil fuel combustion [8]. However, unlike fossil fuels, which are 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 [9]. 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 [10–13]. The broader issues of the supporting hydrogen production and infrastructure needed to support FCV are not considered here though a useful overview is given by Schlapbach and Zuttel [14].

A range of different designs is available and 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 [15]. 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 [16]. 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 [17]. A typical vehicle requires between 50 and 80 kW [18]. A major reason for the high cost of the PEMFC is that it requires expensive, and scarce, platinum as the electrocatalyst at both the anode and cathode. This accounts for about 77% of the stack cost [19]. 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 [20]; and in the longer-term, development of Pt-free alternative materials [21]. Other materials challenges such as the membrane are detailed in [22].

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. [23] 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

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 supporting 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 and 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

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 [24], 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.

1.1.1. *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 [25]. 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 [26]. 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 [27]. 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 [28]. 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 [27]. 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 [29].

The first phase of the JHFC ran between 2002 and 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 [30]. A second phase ran from 2006 to 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 [31]. 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 [31]. 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 [32]. Whether this will ambition will be realised is not known.

1.1.2. *The situation in Korea*

Similar to Japan, Korea is particularly reliant on foreign oil imports and imports 97% of its primary energy [33]. 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 [33]. Following the enactment of the Alternative Energy Promotion Act in 1988, the Hydrogen and Fuel Cell R&D program was initiated [34]. Between 1988 and 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 [1]. Since 2003, the size of this investment has been increasing year-on-year, with US$ 110.8 million invested in 2007 alone [34]. 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 [1]. 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 [34]. 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 [35].

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 [36]. 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 3200 FCV cars by 2012 [34], although this was since revised down to 500 cars [37]. Recent reports suggest the new goal is 10,000 FCV by 2015 [38].

1.1.3. *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 [36]. 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 [39].

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 [39]. Various prototype stacks and vehicles have been developed since the 1950s although Qian et al. [40] 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 Ministry of Science and Technology's High Technology Development Program (commonly referred to as the 863 Program), and the National Basic Research Program (also called the 973 Program) [41].

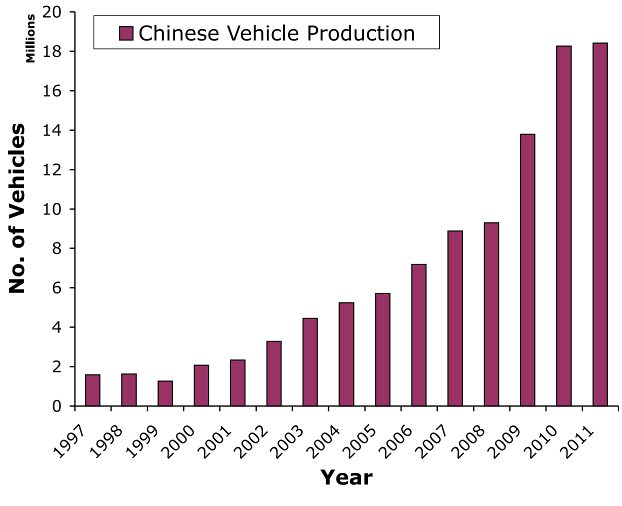

Fig. 1 – Growth in Chinese vehicle production over time. Source: OICA (various years).

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 [42]. Significant amounts of money will be invested, with RMB 50 billion (US $7.6 billion) allocated for R&D and industrialisation [42]. 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) [39], and RMB 75 million per year (2006–2010) [43].

1.2. *Commonalities in approach*

To a large extent, all three countries have adopted a similar framework for trying to encourage FCV deployment. This rests on a combined 'roadmap' strategy that involves the central government, usually represented by the science and industrial ministries, acting as a co-ordinating agency and funder for privileged private and public institutions (typically major car companies, and key research institutes and universities). Specific milestones are identified and a comprehensive approach that involves tackling basic science and practical problems at both the vehicle level and the hydrogen infrastructure level. This follows similar strategies such as the European Union 'HyWays' project and the Californian 'Hydrogen Highway', which aimed to avoid the piecemeal progress that had characterised previous efforts. Differences occur in the degree to which command-and-control strategies are used. In Japan and Korea, the relevant government ministries may set targets and facilitate co-operation but have limited ability to directly affect the decisions of the private companies, whereas the greater role of government in the Chinese economy (and university sector) enables closer alignment.

2. 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 [44]. 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 [45]. 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 separate 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 [46]. The keyword search term used in this paper was "hydrogen fuel cell". The search was conducted so that any records that 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 1965–2011.

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.

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 1960–2011 whilst country specific data was collected over the period 1994–2011. Prior to 1994 both China and Korea have essentially zero fuel cell patents.

3. 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 2011 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 dashed line in Fig. 2 shows the number of articles containing the term "hydrogen fuel cell" published in scientific journals as indexed in the SCIE. 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.

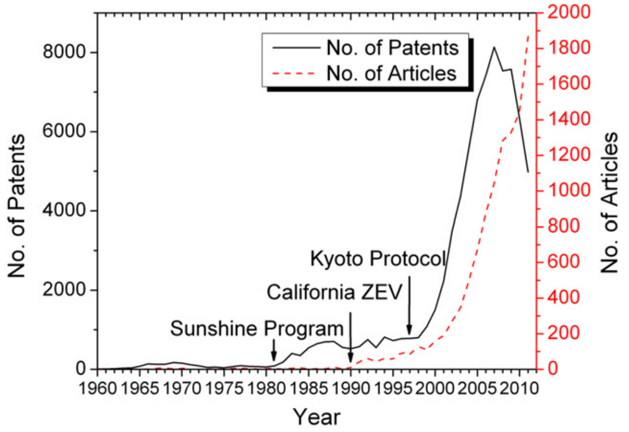

Fig. 2 – The growth in worldwide fuel cell activity as shown by a keyword search of the esp@cenet patent database (solid line) and the SCIE citation database (dashed line). Note the change in vertical scale between patents and articles. Key policy developments are noted on the graph.

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 [44]. 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 4241 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 [47]. Another positive inflection point is seen in 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 [48]. However, a steep downturn in patent activity is observed after 2009. This could be attributed to a number of factors. The first is that it is a methodological error caused by lags in updating the esp@cenet database. To test this, we looked at the results for another search term ("solar cell") and did not observe a similar drop-off. The other possibility is that it marks maturation in the technology. However, the absence of a similar trend in the academic literature and the lack of a commercial FCV at present suggest that this is not the case. The final and most likely hypothesis is that the drop is related in part to the financial crisis of 2008. The lag is due to the time taken for a reduction in funding/activity to convert to a change in patent publication. The USPTO and the EPO typically publish applications around 18 months after filing. A report by the industry journal, Fuel Cell Today, shows that 2006 was a peak year for fuel cell patent applications and that the subsequent years have shown a steep decline [49]. This supports the idea then that the uncertain economic environment has affected private FCV R&D.

The development of fuel cell technology as specifically related to Japan, Korea, and China for the period 1995–2011, 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 Fig. 3.), 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. Again though, the 2008 financial crisis seems to have had a significant effect on patent activity, most notably in Japan and China. Japanese patents decreased by 54% between 2009 and 2011, and in China the decrease was 96%. Of course, some of the same concerns about delays in updating the database remain, but it seems that the crisis must be responsible for some of the decline. Academic research appears unaffected, with China increasing its lead over Japan and Korea since 2009. The resilience of publication activity may be the result of differences in development cycles and funding programs.

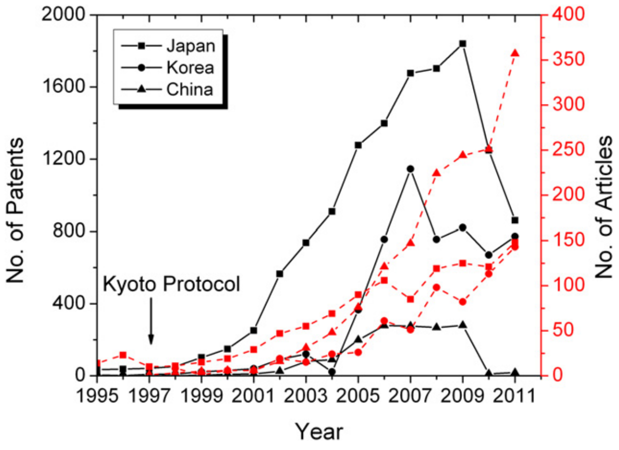

Fig. 3 – The growth in hydrogen fuel cell activity in Japan, Korea, and China as indicated by keyword searching of the esp@cenet and SCIE databases. The patent search-term was "fuel cell NOT biofuel" (solid lines) and the citation search-term was "hydrogen fuel cell" (dashed lines). Note the change in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

The location and concentration of academic activity in each of the three countries can be seen in Table 2. The table shows that in each of the three countries the most productive institution, in absolute terms, is a national research institute which was specifically identified as a key focus for fuel cell research by the relevant policy document. It should be noted though that whilst the Chinese Academy of Sciences (CAS) is regarded as one entity within the SCIE database, it actually consists of 117 different research institutes and over 100 other key laboratories covering the whole spectrum of natural science and technology [50]. It is therefore much larger than

Table 2 – The most productive institutions in each country in terms of publication amount for the period 1995–2011.

Country	Institution	Record count	% of country total
Japan	Inst. Adv. Ind. Sci. Technol.	129	11.8
	Tokyo Inst. Technol.	78	7.2
	Tohoku Univ.	75	6.9
	Kyushu Univ.	72	6.6
	Kyoto Univ.	71	6.5
	Univ. Tokyo	67	6.2
	Nagoya Univ.	40	3.7
	Hokkaido Univ.	34	3.1
	Osaka Univ.	29	2.7
	Nagoya Inst. Technol.	27	2.5
Korea	Korea Adv. Inst. Sci. Technol.	93	14.2
	Korea Inst. Sci. Technol.	79	12.1
	Seoul Natl. Univ.	75	11.5
	Korea Inst. Energy Res.	64	9.8
	Korea Univ.	52	8.0
	Yonsei Univ.	49	7.5
	Hanyang Univ.	28	4.3
	Korea Res. Inst. Chem. Technol.	24	3.7
	Ajou Univ.	23	3.5
	Sungkyunkwan Univ.	22	3.4
China	Chinese Acad. Sci.	334	21.7
	Univ. Sci. Technol.	118	7.7
	Harbin Inst. Technol.	80	5.2
	Tianjin Univ.	68	4.4
	Shanghai Jiao Tong Univ.	65	4.2
	S. China Univ. Technol.	56	3.6
	Tsinghua Univ.	50	3.2
	Zhejiang Univ.	50	3.2
	Nanjing Univ. Technol.	49	3.2
	Tsing Hua Univ.	48	3.1

any single one of the institutes or universities listed. This partly explains the much greater academic productivity shown by the CAS.

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 and 2011 was 18.11 for Japan, 13.94 for Korea, and 11.40 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.

3.1. *Patenting behaviour and collaboration patterns*

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. Considering data unaffected by the 2008 crisis then in 2009 for example, of 381 patents published by Chinese inventors, 34% named a university as the applicant, and a further 18% named a government research institute. This means that private companies and individuals were only responsible for 48% of published patents. 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. In Japan, just 1% of 2009 patents featured a Japanese university in the filing, and only five patents were granted to Japanese research institutes. The companies that are most heavily involved in fuel cell activity, as indicated by patents published in 2009, are shown in Fig. 4. The companies are colour coded according to industrial sector, with blue representing vehicles, orange representing electronics, and green representing chemicals. The greatest activity is taking place in the PEMFC vehicle sector, which represents about 38% of fuel cell patents published in Japan. This marks a change from the situation before 1997 when more patents were being filed by utilities companies such as Tokyo Gas, and Tokyo Electric Power Company, as they developed high temperature fuel cells for stationary and home power generation.

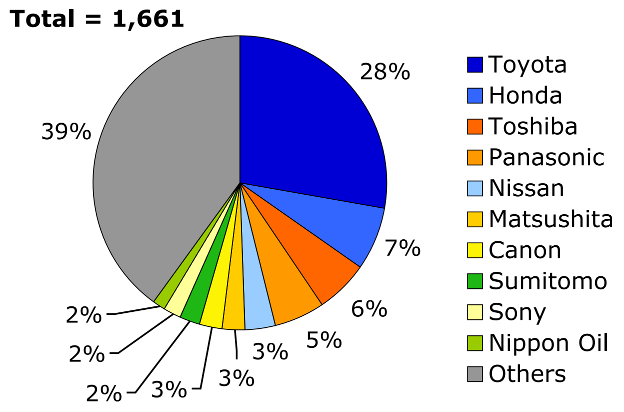

Fig. 4 – The top ten producers of fuel cell patents in Japan for the year 2009. Companies are colour-coded according to industrial sector: blue for vehicles, orange for electronics, and green for chemicals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In Korea, where the total number of patents granted was about half that of Japan, the percentage granted to universities was higher, at 5%. Research institutes such as the Korean Advanced Institute for Science and Technology (KAIST) and the Korean Institute for Energy Research (KIER), featured more prominently with 13% of patents. Amongst the private companies, patent filing was dominated by the *chaebols* such as the car manufacturer the Hyundai Group with 31%, and then the electronics firms such as the Samsung Group with 21% and the LG Group with 5%.[1] A smaller firm called Fuel Cell Power Inc. was responsible for 3% of 2009 fuel cell patents. In general, the Korean market seems to have less diversity than the Japanese market, as indicated by the numbers quoted. The dominance of both Toyota and Hyundai in the respective FC innovation systems accords well with their publicly stated aims to commercialise FCV by 2015 [32,38].

Another interesting aspect that emerges from analysing the patent records for 2009 is the extent of collaboration between the public and private sectors in each country. Whilst the number of patents filed by Japanese academics is small, it shows a high degree of cooperation with industry. Of the 30 Japanese patents filed by academic-related institutions, 48% named a private company in addition to the university or institute. In Korea, the collaboration figure was 16%, although this may be partly affected by the larger absolute number of academic-related patents filed. In China however, zero collaboration between academic institutions and industry was found amongst the patent records. Of course, patent applications are only one method of estimating the degree of cooperation between individuals, institutions, and sectors, and it is highly likely that other forms of cooperation are taking place. Within the specific context of the fuel cell field and focussing on patent data as one means of evaluating the innovation process, then the information related here does provide some insights into the approach being adopted in the different countries and the success, or otherwise, of the policies being promoted. It is also noted that it may be possible that patents filed by individuals, which is partly a result of work conducted during academic employment, are not identified. The specific policies that govern intellectual property rights within different nations and institutions vary significantly and are perhaps responsible for some disparity and inaccuracy in the figures.

Understanding the rationale behind the different patterns of patenting activity and collaboration between industry and academia in the different countries requires a more detailed description of the educational, legal, political, and economic systems that exist in each country than it is possible to discuss here. However, within the confines of the specific topic of fuel cell innovation, the results that have been presented here detail some features of each country's innovation system that have previously been observed. In recent years, a particular view of the role of universities in innovation systems has emerged, which has encouraged individual researchers and

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[1] *Chaebol* is a term used to refer to the major Korean family-run conglomerates that comprise a broad range of companies and services and exert a major influence on the Korean economy.

universities to take greater responsibility for patenting and ‘spinning-out’ ideas and inventions which occur within the lab. Simultaneously, there has been greater encouragement to secure more funding from industry and foundations through joint projects and sponsored research, partly as a way of reducing public spending. This view of universities has been particularly favoured in the US where measures such as the Bayh-Dole Act 1980, which allowed universities to patent federally-funded innovations, and the National Cooperative Research Act of 1984, which relaxed anti-trust rules to allow joint ventures, were legislated to achieve these aims [51]. A similar shift in policy has also taken place in the UK university sector [52]. This system of university-industry-government interactions is referred to as the triple-helix model of innovation [53]. Until recently, the situation in Japan was quite different, with university professors and universities given little incentive to patent inventions emerging from their research [54]. The adoption of a Japanese version of Bayh-Dole Act in 1999 and the legal incorporation of universities that took place in 2004 has started to change that situation [54]. Japan has also historically, had a greater proportion of R&D funded and undertaken by industry [54]. This institutional context perhaps explains the results seen in Fig. 4, which shows the minimal influence of universities and research institutes on fuel cell patents, and the large influence of major car and electronics firms.

Korea has closely followed Japanese development policies, but usually with a lag of 20–30 years in relation to R&D policy [55]. Up until the 1990s, Korean universities mainly acted as training centres to meet industrial needs rather than focussing on innovative research in their own right [56]. Changes were introduced to the university system such as the ‘Brain Korea 21’ program in 1998 that promoted greater research intensification and international publication [57]. The greater activity of Korean universities and research institutes in the patent system, along with significant collaboration with industry, indicates that there may be greater dynamism and cross-fertilisation in the FC field in Korea than Japan.

There are difficulties in assessing the patent performance of Chinese universities and businesses, which still operate in a strongly state-controlled economy, with respect to the economic policies of Japan and Korea. The low overall level of patent activity in the FC area, compared with academic publications, as shown in Fig. 3, combined with the low degree of private industry involvement in patents, reflects a number of institutional factors that are particular to China. Firstly, the intellectual property rights (IPR) regime in China is still quite new (its patent law was enacted in 1984) and the legal system is generally weak, with poor enforcement [58]. This creates a disincentive for researchers and firms to engage in innovation activity and then to patent new inventions and processes. Secondly, there is a question as to why the proportion of patents filed by universities is comparatively large but with no industry collaboration. This may be explained by the different structure and innovation policy objectives that exist in the Chinese university sector. For example some of China’s biggest companies were established and operated by universities (the Founder Group from Peking University, and Lenovo from the CAS) [59,60]. This ‘university-run enterprise’ (URE) structure, as described in [60], provides a different innovation pathway from Japan and Korea, and compensates for the stricter regulation regarding the roles of universities, state-owned companies, and private industry, and how they can interact. However, the URE model has already shown signs of decline as the private sector has started to develop [60].

3.2. *Limitations of the use of publication and patent data*

Bibliometric analysis has a number of criticisms. The most notable is that ‘pressure to publish’ can lead to a large quantity of articles which have only marginal novelty – this is addressed somewhat by the inclusion of the ISI ‘impact factor’. A second criticism is that ‘buzz’ can lead researchers to repackage tangential or unrelated work to fit within a ‘hot’ topic, such as fuel cells. This could artificially increase the apparent activity. Despite these criticisms, Motoyama and Eisler [61] argue that such analysis can still be useful in evaluating innovation, although they caution that it should not be the only criteria used. Patents also 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 [62]. 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 [63]. However, it remains a useful quantifiable measure of the success of policy in encouraging innovation, and as Dernis and Kahn [62] 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. Therefore, the extent of publishing in local languages is missing. However, it seems unlikely that incorporating these publications would affect the general trends observed here and the growing use of English as a *lingua franca* in scientific publishing means that more articles are increasingly being published in English by Asian researchers.

3.3. *FCV and the diffusion model*

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 [44] and Utterback and Abernathy [64], 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. It could be argued that this behaviour is seen in the Chinese case where there has been rapid growth in academic publications but relatively slow growth in patents. Given that the Chinese technical base was at a lower level at the start of the 1990s then initially, advances in knowledge were concentrated in the university sector and gradually that is transferring to the commercial sector. Whilst the greater patent versus publication activity in Japan and Korea may suggest that FCV as a technology class are progressing along the diffusion curve, the failure of previous vehicle pilot schemes and the ongoing 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. [63] have found a similar correlation across a range of renewable technologies using a slightly different methodology. Although, as Schilling and Esmundo [65] 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 on 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. Alongside this, the changes in innovation policy that have been mentioned [54,57,60], which put a greater emphasis on patenting and international journal publication overall, are also likely to have had an effect. 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, 51% are from universities indicates that there is still considerable room for the private sector to grow in FCV development.

The effect of the financial crisis on FCV development appears to be significant and it is difficult to predict what the long-term impacts will be. Whilst the industry journal, *Fuel Cell Today*, was optimistic that patenting, and by association technological progress, would resume promptly but perhaps at a lower rate than in the previous decade [49], there are some causes for concern about this optimism. The first is that the sharp drop in fuel cell patents, shown in Figs. 2 and 3, indicates that investment in this area is unstable and is viewed as expendable in times of financial uncertainty. If FCV were viewed as a near-term profit centre for the industry then it might be expected that greater efforts would have been made to sustain progress, and by association patent production. This instability is particularly troubling in the case of China as it was relatively unaffected by the financial crisis, experiencing only a drop in GDP growth (from 13% in 2007 to 6.8% in 2008) rather than the recessions experienced in Japan and Korea [66]. The second concern is that despite the counter-cyclical stimulus packages, which were adopted in response to the crisis with an explicit aim of trying to promote a ‘green’ economy, fuel cell patent activity hasn’t responded. Korea for example, allocated 95% of its $38.1 billion stimulus package towards ‘green’ technology research and other initiatives, whilst China pledged about $216 billion for such measures [67]. Whilst it is not clear how much of those funds went towards FCV development, they indicated a desire to create an environment friendly to such technology. The divergence between the patent data and the publications data suggests that this funding has enabled academic research to continue but has not been as effective in the private sector.

4. Technology and policy recommendations

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 [32,37,42]. 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. Here, we discuss some recommendations aimed at both the research community and government decision-makers which may help encourage a transition to occur.

1. Providing a stable investment climate post-Kyoto and developing more sophisticated indicators of technological progress. The Kyoto Protocol on Climate Change provided a degree of certainty that encouraged the planning and development of low-carbon technology, as suggested by the data in Figs. 2 and 3. With the agreement due to expire in 2012, and the continued financial uncertainty, then governments need to provide industry and researchers with clear signals as to their future priorities in this area, as well as support, if the progress observed and momentum created in FCV is not to be lost. Coupled with this is the need to find better ways of evaluating progress. The patent and bibliometric data used here is one method but it could be developed further and combined with learning curves and other economic measures to give a more comprehensive estimate of progress.
2. *The use of ‘**design complexity**’ analysis to model the connectivity between the different components of the FCV and identify technical bottlenecks*. This approach, described more fully by McNerney et al. [68], suggests that designs which have a higher degree of modularity (lower connectivity) allow for faster long-term improvement. The generalisability of the approach means that it can act as a design tool to speed innovation at multiple levels of a product – from catalyst design to systems integration. The reduction in search efforts could aid scientists in designing their experiments and aid policymakers in targeting funding and evaluating progress.
3. Re-evaluating the success of the triple-helix innovation policy approach for promoting disruptive technologies. As

described earlier, and confirmed by studying the patent data, there are clear linkages between universities, industry, and government in FCV development. This coordinated approach has produced many improvements in terms of improving power output, decreasing stack costs, and ensuring logical provision of supporting infrastructure such as hydrogen refuelling stations as well as understanding consumer preferences. However, the continued missed deadlines suggest that a new approach may be needed. The current paradigm assumes that the existing dominant industry is best placed to manage its own destruction in the sense of transitioning from fossil-fuel-based combustion engines to hydrogen fuel cells. This may be frustrating the process of 'creative destruction' identified by Schumpeter as so important for technological progress [69]. Considering previous transitions in transportation technology, such as moving from hay-fed horses to coal-fired steam trains, then it seems that initially the usurping technology (the steam train) was allowed to grow in a non-competing transport niche (long-distance freight vs. short-distance passengers). It was only later that the train eventually came to cannibalise the horse-and-cart passenger market. There is an argument that the current strategy is relying on the incumbent to design its successor which may allow them greater stability (and profitability) but may not be encouraging faster progress towards the social optimum of a new transportation technology which produces less air pollution and lower CO_2 emissions. Within the context of fostering new technologies such as FCV to enable sustainable development, Ashford and Hall outline an update of this Schumpeterian creative destruction [70].

4. *New methods for producing hydrogen after the Fukushima nuclear disaster*. While not directly related to encouraging fuel cell innovation, there is a long-running associated issue of how the hydrogen fuel can be produced cleanly and efficiently. Currently, most H_2 for FCV is obtained from steam reforming of natural gas but it had been hoped that thermal splitting of water by nuclear fission reactors could provide a more sustainable source of H_2 [71]. Particularly in Japan, support for new nuclear plant construction has declined significantly after the Fukushima nuclear disaster in March 2011 [72]. Whilst it is likely that nuclear fission will continue to play a role in the Japanese electricity sector, and that of many other countries, it seems sensible to encourage greater development of other hydrogen production routes such as from photoelectrochemical cells, solar thermal, geothermal or wind energy [71].

5. 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 here in 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 better-established programs in Japan. The concentration of publications within national research centres/academies indicates the success of the targeted policy approach. However, the repercussions of the 2008 financial crisis appear to have had a serious negative effect on private R&D efforts in the fuel cell area, which may lead to significant delays in achieving commercialisation. The methodological approach used in our analysis shows a clear indication of general trends in FC technology, the question of whether FCVs are ultimately constrained by technical limitations or the lack of appropriate supporting policy remains, largely, 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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