INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 36 (2011) 6957–6969

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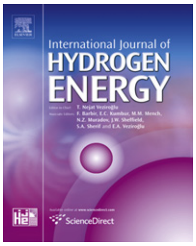

Technology forecasting and patent strategy of hydrogen energy and fuel cell technologies

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ARTICLE INFO

Article history:
Received 6 January 2011
Received in revised form
10 March 2011
Accepted 11 March 2011
Available online 13 April 2011

Keywords:
S-Curves
Hydrogen energy
Logistic growth curve
Patent strategy
Fuel cell

ABSTRACT

This study presents the technological S-curves that integrates the Bibliometric and patent analysis into the Logistic growth curve model for hydrogen energy and fuel cell technologies and identifies the optimal patent strategy for the fuel cell industry, including PEMFC, SOFC, and DMFC/DAFC. Empirical analysis is via an expert survey and Co-word analysis using the United States Patent and Trademark Office database to obtain useful data. Analytical results demonstrate that the S-curves is a highly effective means of quantifying how technology forecasting of cumulative publication patent number. Analytical results also indicate that technologies for generating and storing hydrogen have not yet reached technological maturity; thus, additional R&D funding is needed to accelerate the development of hydrogen technology. Conversely, fuel cell technologies have reached technological maturity, and related patent strategies include freedom to operate, licensing, and niche inventions. The proposed model can be applied to all high-technology cases, and particularly to new clean technologies. The study concludes by outlining the limitations of the proposed model and directions for further research.

1. Introduction

The rapid growth in consumption of fossil fuels has accelerated their depletion. Fossil fuel reserves are diminishing rapidly across the world, intensifying the stress on existing reserves day-by-day due to increased demand. Not only that, fossil fuels, presently contributing to 80% of world primary energy, are inflicting enormous impacts on environment. Climatic changes driven by human activities, in particular the production of greenhouse gas emissions, directly impact the environment. A secure and accessible supply of energy is thus very crucial for the sustainability of modern societies [1]. Hydrogen energy is a valuable high-quality, non-polluting and safety fuel [2]. In addition, hydrogen production represents one of most promising solutions for solving the problem of intermittence in the power production by renewable sources by reducing local impacts of energy conversion and diverting it to several final uses. Unlike the fuels used today, it is free of carbon; as a result, no climate-influencing carbon dioxide is released during combustion or use in a fuel cell [3]. Thus, it has long been included in the International Energy Agency (IEA) plan as a major component of clean energy systems and is predicted to account for 50% of total energy consumption by 2050 [4].

Hydrogen can be produced from natural gas, coal, hydrocarbons, biomass and even municipal waste by using a variety of techniques, as well as by splitting water. Such diversity significantly contributes to the security of fuel supply. Fuel cells convert either hydrogen or a hydrogen-rich fuel and an oxidant (usually pure oxygen or oxygen from air) directly into electricity by using a low-temperature electrochemical process. While

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doi:10.1016/j.ijhydene.2011.03.063

operating with hydrogen or hydrogen-rich fuels, fuel cells potentially play a major role in catalyzing the transition to a future sustainable energy system with low CO_2 emissions (Fig. 1) [5–7]. Hydrogen is produced in large quantities by steam reformation of hydrocarbons, generally methane. This method yields CO_2 as a by-product, yet does not burn the same amount of methane. Hydrogen can also be produced by splitting water through various processes, including electrolysis, photo-electrolysis, high-temperature decomposition and photo-biological water splitting. The commercial production of hydrogen by electrolysis of water achieves an efficiency of 70–75%. However, hydrogen produced by this route costs several times higher than that produced from fossil fuels [8,9]. Fig. 2 illustrate the production cost of hydrogen energy. The hydrogen energy industry is currently focused on chemical, petrochemical, metallurgy and electronic processes, with applications largely in experimental and emerging stages. Many companies worldwide have invested in hydrogen energy and now offer a wide variety of products that use hydrogen energy. However, none of these products has reached the scale of mass production. Conversely, most hydrogen energy products on the market are substitute products; that is, explain what a substitute product is. A substitute product, as opposed to a complementary product, has a positive cross elasticity of demand, implying that a product's demand increases as the price of another product increases. Conversely, the demand for a product decreases as the price of another product decreases. Classic examples of substitute goods include margarine and butter, petroleum and natural gas (used for heating or electricity), and traditional oil car and fuel cell car. The fact that a product is substitutable for another has immediate economic consequences. Restated, insofar as a product can be substituted for another, the demand for the two products are bound together since consumers can trade off a product for another one if it

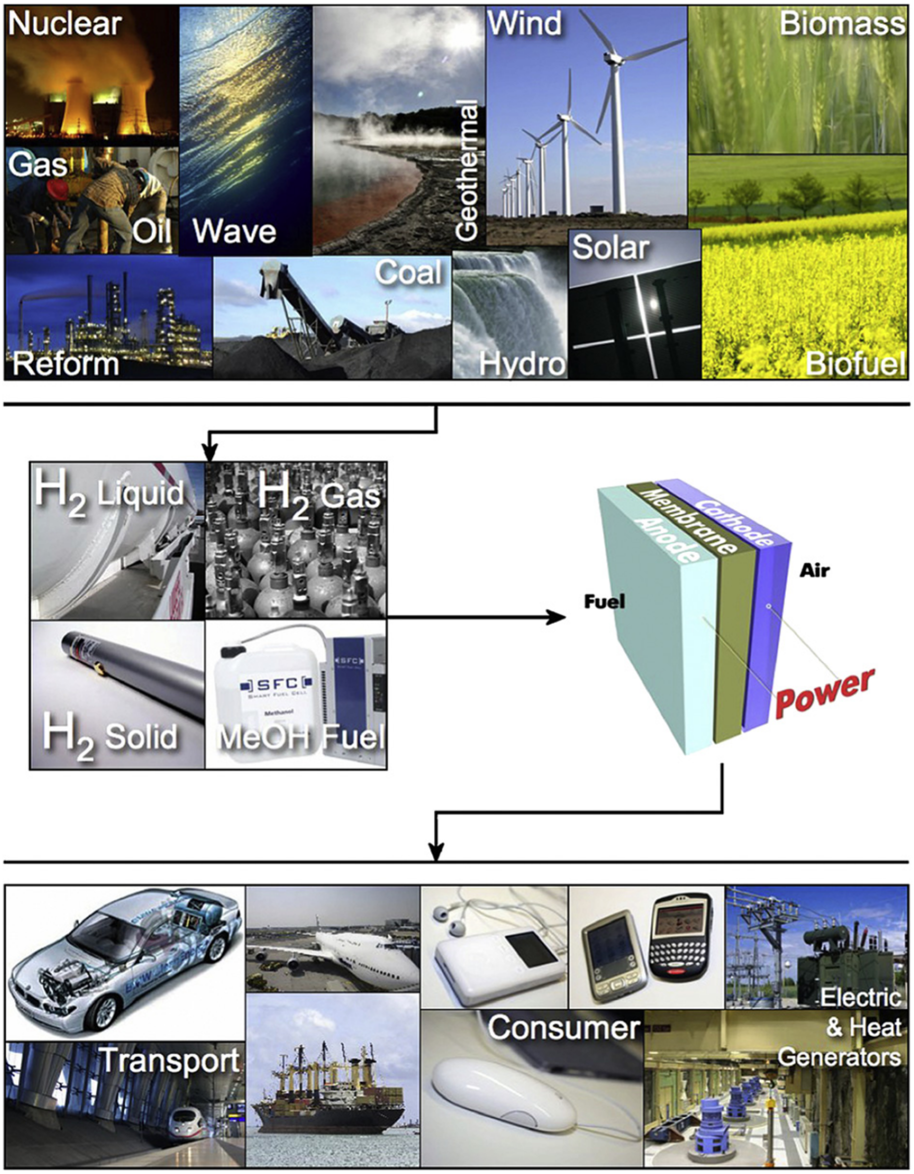


Fig. 1 – Hydrogen as an energy carrier linking multiple production methods and sources to various fuel cell applications. *Source*: Edwardsa et al. [7].

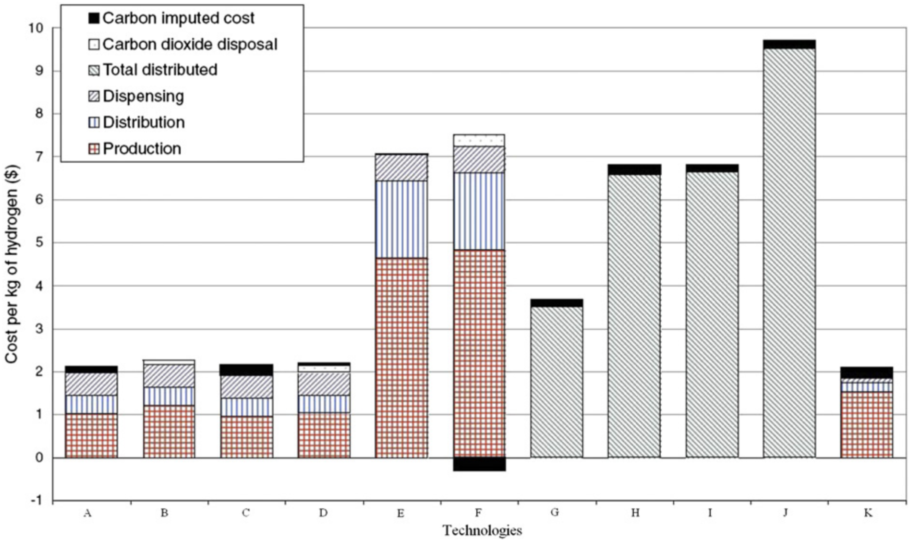


Fig. 2 – Production cost of hydrogen technology. *Source*: Michael and Martin [10].

becomes advantageous to do so. Before consumer demand for such substitute products increases and their costs reduce, commercial scale demand is not foreseeable in the near future. Fig. 3 present the technology trajectories foreseen by the European Union, Japan, and the United States in terms of hydrogen and fuel cells strategies. Furthermore, the revised version has added a new table (Table 1) to summarize the forecast of several roadmaps for deployment status and targets for hydrogen technologies and fuel cell applications. In sum, the current visions, roadmaps, and public/private programs for hydrogen and fuel cell technologies focus on research, development and demonstration (RD&D) and market preparation. These programs have been successful in forming technology-specific coalitions, attracting businesses, and defining common objectives. A preoccupation with technological readiness has limited attention to the dynamics of market entry. Therefore, understanding the technological development of hydrogen energy and predicting its future trends will prove useful when formulating strategies for hydrogen energy development.

The importance placed on research into growth curve models, such as the logistic curve model, for examining technology diffusion and substitution has increased in the last few decades. The growth curve model involves fitting a growth curve to a dataset of technological performance. The growth curve beyond the data range is used to estimate future performance. For instance, Frank [11] utilized the logistic curve model to forecast the diffusion of wireless communications in Finland and to identify the factors affecting the diffusion process. The logistic curve model followed the means of nonlinear least squares method after identifying two parameters of the logistic curve model as functions of certain variables. Analytical results demonstrated that the economic situation affected the relative growth rate, and that wireless network coverage affected the number of potential adopters. Schilling and Esmundo [12], who analyzed renewable energies (REs) using such a technology S-curve perspective, identified some important implications for both governments and industry. Their empirical analysis was based on data for government R&D investment and technological improvement (in the form of cost reductions). Schilling and Esmundo demonstrated that both wind energy and geothermal energy are poised to become more economical than fossil fuels within a relatively short time frame. Additionally, the evidence further suggests that R&D for wind and

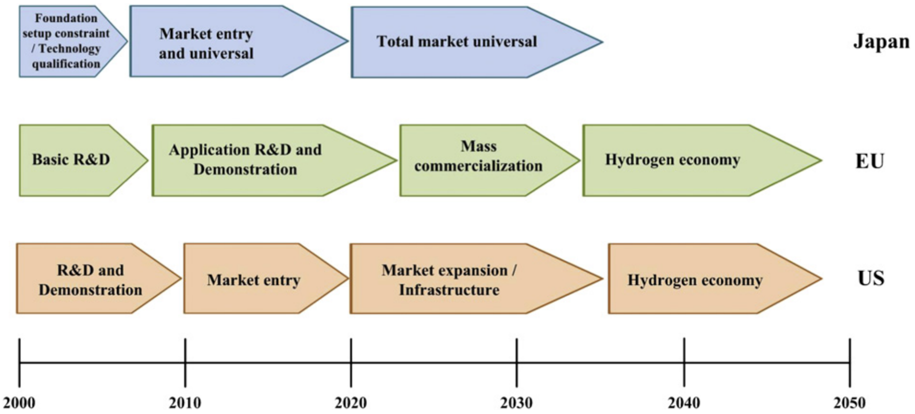


Fig. 3 – Technology trajectories foreseen by EU, Japan, and US hydrogen and fuel cells strategies.

Table 1 – Roadmaps of deployment status and targets for hydrogen technologies and fuel cell applications.

Technology	Today	2020–2025	2050
Carbon capture and sequestration (CSS) (€/ton CO_2)	20–30	4–8	3–6
Hydrogen produced from coal with CCS (€/GJ)	8–10	7–9	3–5
Hydrogen transportation/storage cost (pipeline, 5000 kg/h, 800 km) (€/GJ)	10–15	3	2
PEMFC (€/kW)	6000–8000	400	40
High-temperature fuel cells (€/kW)	8000–10,000	800	200
EU–portable fuel cells sold per year	N/A	250 million	N/A
EU–fuel cell vehicles sold per year	N/A	0.4–1.8 million	N/A
EU–stationary fuel cells (CHP) sold per year	N/A	2–4 GW	N/A
Japan–cumulative sale target of fuel cell vehicles	N/A	5 million	N/A
IEA forecast–global fleet of fuel cell vehicles	N/A	N/A	700 million

Source: Edwardsa et al. [7].

geothermal technologies has been underfunded by governments compared with funding for solar technologies, and government funding of fossil fuel technologies may be excessive given the diminishing performance of those technologies. Chu et al. [13] compared the performance of three conventional models, namely, the Gompertz, Logistic and Bass models, to identify the most appropriate model and identify the forces driving the diffusion rate. Empirical results indicated that the Logistic model performed best. Network externalities, which this study shows to be the same as the imitation effect in the Bass model, explain the superiority of the Logistic model. Dergiades and Dasilas [14] modeled and examined the diffusion process of the mobile telecommunication services in Greece economy by using Logistic and Gompertz model. Lee and Cho [15] also used and extended Frank's [11] Logistic model to examine the diffusion of the mobile telecommunication services in Korea. In addition to the Logistic model, the authors used an autoregressive moving average model. The results demonstrated that the Logistic model fitted better than the autoregressive moving average model.

However, predicting the development of technologies is rather difficult as historical data are typically unavailable for new clean energies. Many studies have integrated Bibliometric analysis of publications and patent data with growth curve methods for forecasting the new technologies. Bibliometric analysis is defined by Norton [16] as the measurement of literatures and texts. The approach is to capture some of the information inherent in the content and patterning of the literature. Bibliometric analysis uses counts of publications, patents, or citations to measure and interpret technological advances [17]. Three major forms of Bibliometric analysis have emerged—Citation analysis, Patent analysis, and Publication analyses [18]. Notably, Bibliometric can be utilized to understand the past and potentially forecast the future [19,20]. Historically Bibliometric analyses have been used to trace back academic journal citations. Nowadays, the Bibliometric ayalysis, which was recently applied to solve this problem, can provide an interesting alternative data source for quantitative evidence of R&D activity and text materials [17,21–24]. For instance, Cheng and Chen [24] applied the growth curve method to investigate the technological performance of nanosized ceramic powders. That study applied Bibliometric analysis to the engineering index (EI) database and the United States Patent and Trademark Office (USPTO) database to acquire useful data. The principal finding was that nanosized ceramic powders were all in the initial growth periods of their technological lifecycle. Bengisu and Nekhili [23] demonstrated steady growth for 20 emerging technologies using the Turkey by S-curves method. To summarize, Bibliometric analysis could provide a nicely accessible and cost-effective data or information. It helps to explore, organize and analyze amounts of historical data helping researchers to identify

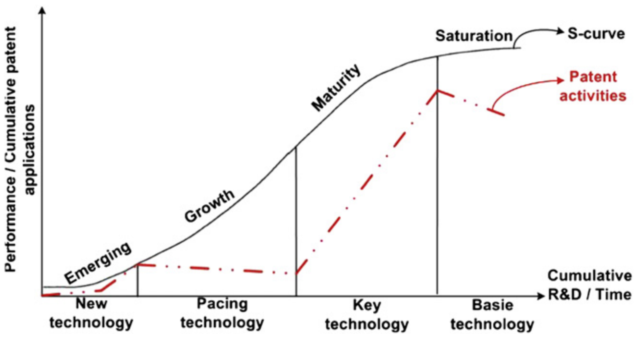
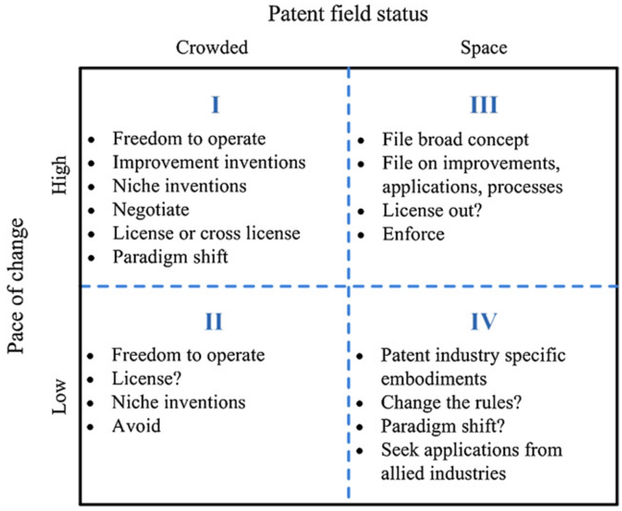


Fig. 4 – Scheme of integration for technological S-curve and patent activities. ***Source*****: Ernst [30].**



Pace of change	Patent field status: Crowded	Patent field status: Space
High	I • Freedom to operate • Improvement inventions • Niche inventions • Negotiate • License or cross license • Paradigm shift	III • File broad concept • File on improvements, applications, processes • License out? • Enforce
Low	II • Freedom to operate • License? • Niche inventions • Avoid	IV • Patent industry specific embodiments • Change the rules? • Paradigm shift? • Seek applications from allied industries

Fig. 5 – Scheme of patent strategy matrix. ***Source*****: Berkowitz [31].**

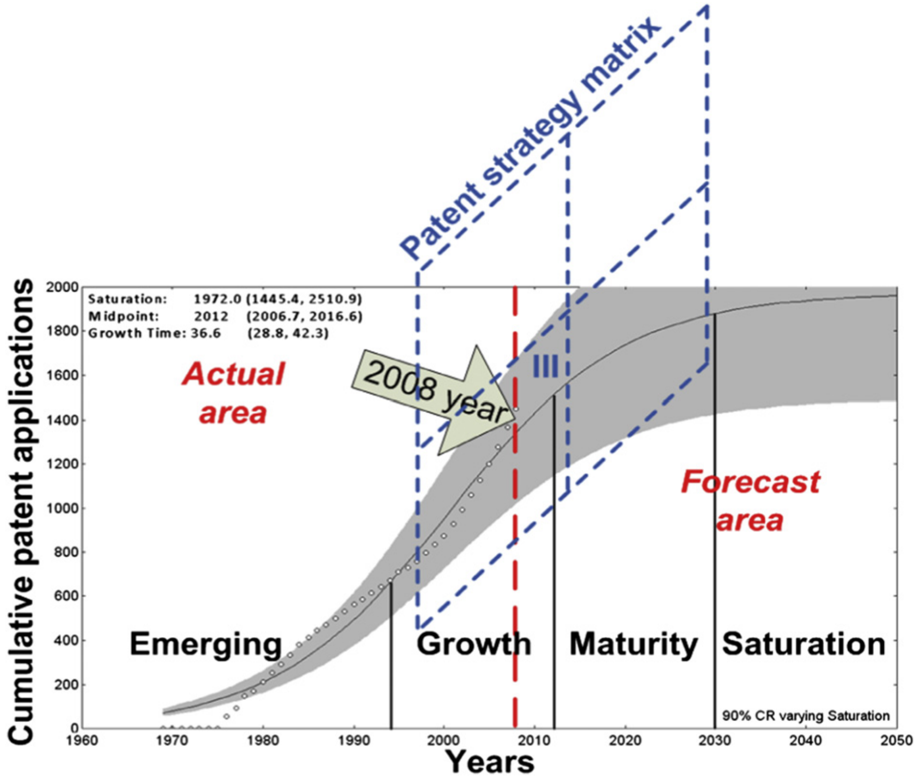


Fig. 6 – The growth curve of hydrogen generation technology.

"hidden patterns" that may help researchers in the technology forecasting and decision making process [17,23]. Chen et al. [25] predicted the technological S-curves for hydrogen energy and fuel cell technologies by integrating bibliometric analysis into the Logistic growth curve model. In the study, which used the most suitable keywords linked to the technologies in question and determined the number of publications and patents in those fields. Useful data for this study were

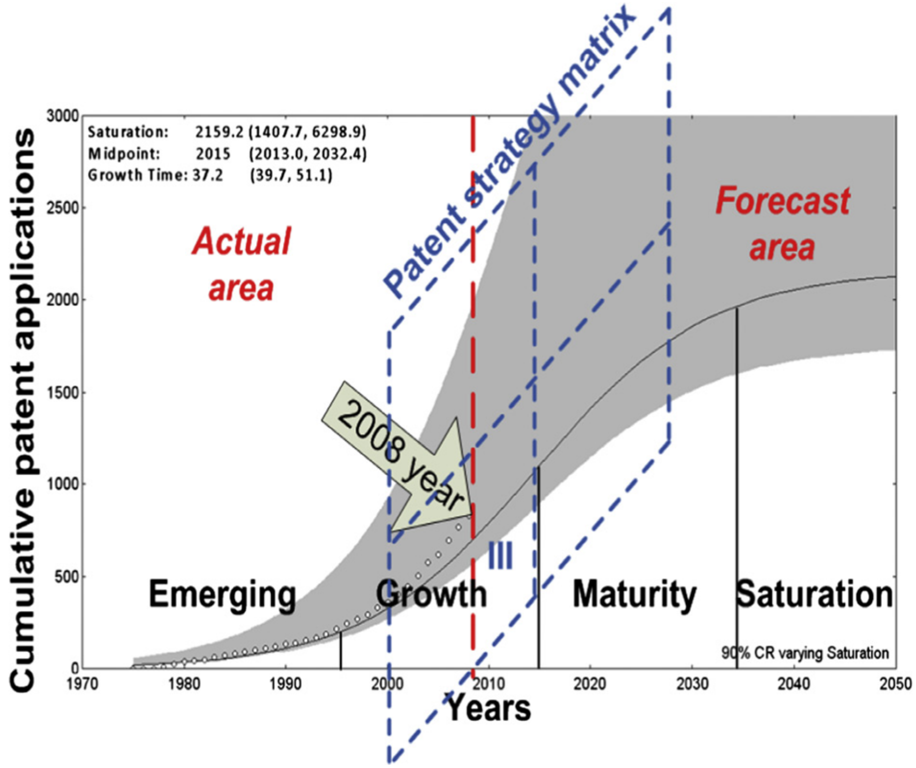


Fig. 7 – The growth curve of hydrogen storage technology.

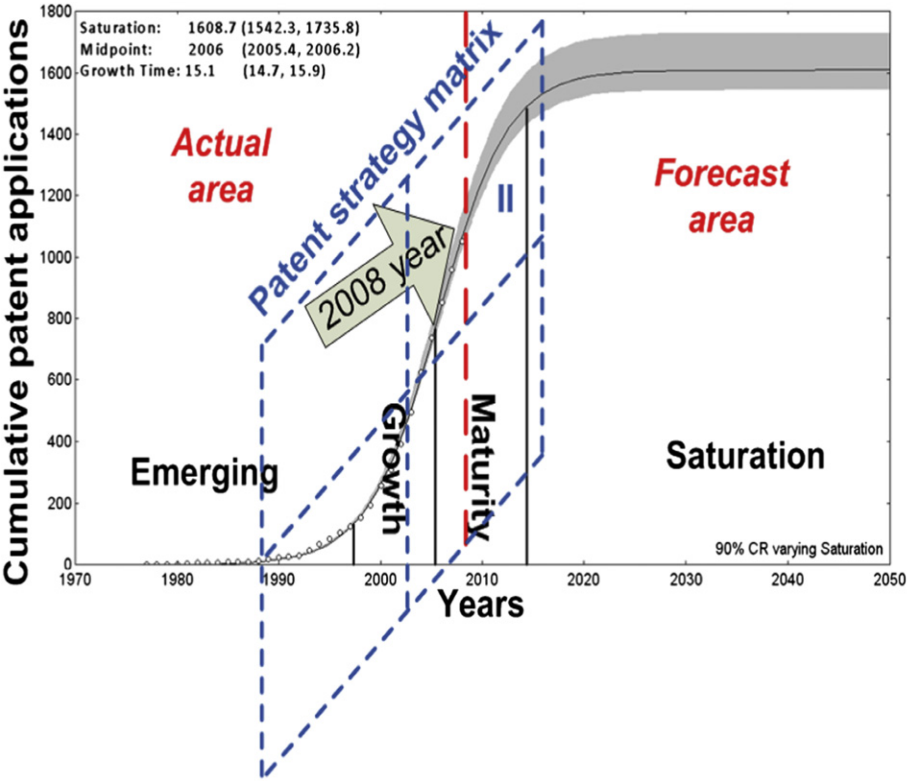


Fig. 8 – The growth curve of PEMFC technology.

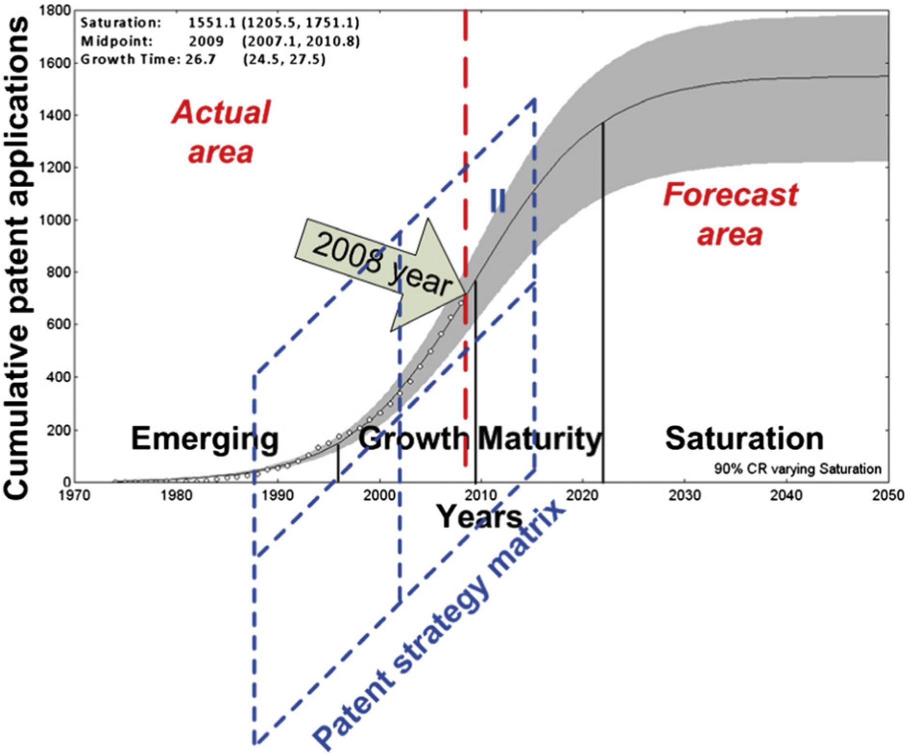


Fig. 9 – The growth curve of SOFC technology.

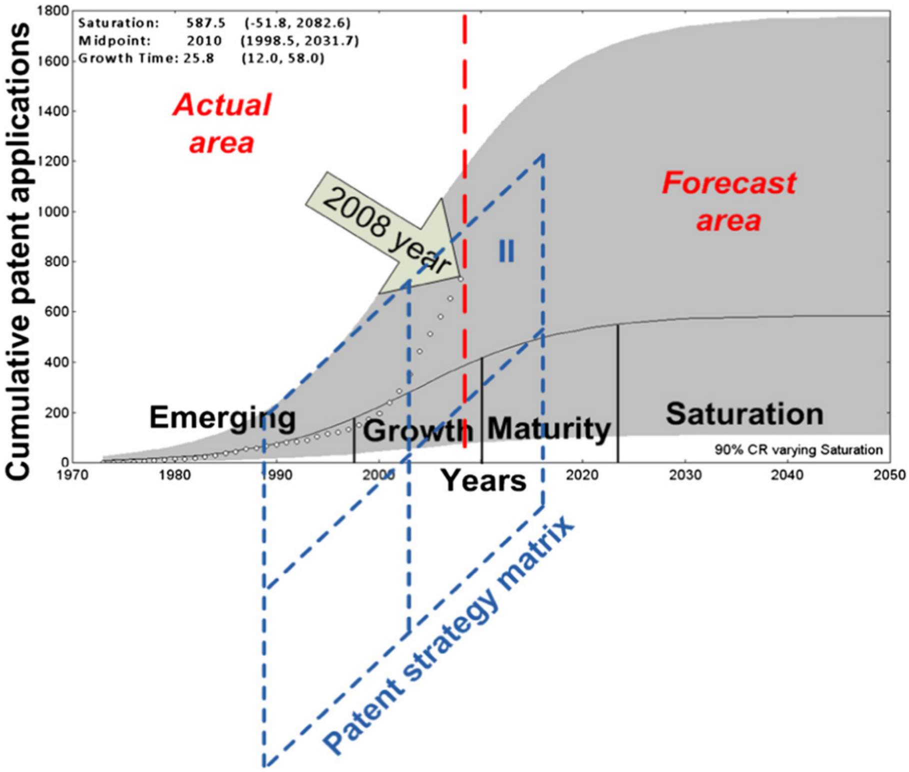


Fig. 10 – The growth curve of DMFC/DAFC technology.

obtained through Bibliometric analysis of publications and patents. The number of scientific publications and patents in most technologies investigated were strongly correlated.

Therefore, this study applied the growth curve method to investigate the performance of hydrogen energy technologies, which includes generation, storage, the proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), and direct methanol fuel cell/direct alcohol fuel cell (DMFC/DAFC). This study applied Bibliometric analysis to the USPTO database to obtain useful data; expert survey and co-word analysis were also utilized for data collection. Besides, this study assumes diffusion of hydrogen technologies, as measured by number of patents and publications, follows the well-known S-curve of natural growth. In addition to investigating the technological performance of hydrogen energy and fuel cell by applying the Logistic growth curve model, this study presents patent strategies for the fuel cell industry. The remainder of this paper is organized as follows. Section 2 describes the foundations of the growth curve method and patent strategy matrix. Section 3 explains survey design and identifies data sources. Section 4 presents empirical results. Section 5 offers conclusions.

Table 2 – Parameters and accuracy of the logistic fits for all technologies.

	Logistic fits												Congruence analysis	
	Midpoint (t_m) [years]				Growth time (*dt*) [years]				Saturation (*k*) [numbers]				R^2	Significance[d]
	Value[a]	Min[b]	Max[b]	Error[c]	Value[a]	Min[b]	Max[b]	Error[c]	Value[a]	Min[b]	Max[b]	Error[c]		(*Prob.* > *F*)
Generation	2012	2006.7	2016.6	0.002	36.6	28.8	42.3	0.184	1972.0	1445.4	2510.9	0.270	0.875	0.000
Storage	2015	2013.0	2032.4	0.005	37.2	39.7	51.1	0.153	2159.2	1407.7	6298.9	1.133	0.892	0.000
PEMFC	2006	2005.4	2006.2	0.000	15.1	14.7	15.9	0.040	1608.7	1542.3	1735.8	0.060	0.989	0.000
SOFC	2009	2007.1	2010.8	0.001	26.7	24.5	27.5	0.056	1551.1	1205.5	1751.1	0.176	0.949	0.000
DMFC/DAFC	2010	1998.5	2031.7	0.008	25.8	12.0	58.0	0.891	587.5	−51.8	2082.6	1.817	0.977	0.000

Notes.
a Estimated by logistic growth method.
b Estimated by the bootstrap method with 90% confidence level.
c Estimated by the ratio of the average distance of the parameter value from its estimated Min and Max to the parameter value.
d Model congruence at significant at the 5% level. All tests are statistically significant with *p*-Values <0.05.

Table 3 – Lifecycle stage of all technologies.

	Emerging [years]	Growth [years]	Maturity [years]	Saturation [years]	Saturation [numbers]
Generation	1969	1994	2012	2030	1972.0
Storage	1975	1996	2015	2034	2159.2
PEMFC	1977	1998	2006	2014	1608.7
SOFC	1974	1996	2009	2022	1551.1
DMFC/DAFC	1973	1997	2010	2023	587.5

2. Methodology

Forecasting using the growth curves method is based on parameter estimation of the lifecycle curve of a technology. The method is helpful for estimating the level of technological growth or decline at each stage in the lifecycle and in predicting when a technology will reach a particular stage [11,15,17,26–29]. Fig. 4 shows the S-curve concept and patent activities over the technological lifecycle, which has four developmental stages [30]. The emerging stage is characterized by a relatively slow technological growth compared with the amount of R&D effort. During the growth stage, marginal technological progress divided by cumulative R&D expenditures is positive, and is negative during the mature stage. During the saturation stage, small technological performance improvements are gained only through considerable R&D efforts.

Fig. 5 presents the patent strategy matrix for each lifecycle stage in technological development [31]. As a partial framework for focusing on patent strategy, the two most important variables are the degree of prior patenting in a field, occasionally referred to as “how crowded the field is” and the rate of change in the field. Change can either be expressed on a learning curve on the science or a shift in the marketplace need, such as a new priority for environmental cleanliness or energy efficiency or a developing scarcity. The two variables are arrayed in a two-by-two matrix and four possible situations are defined. Obviously, the full picture requires full definition of the business strategy and sources of a competitive advantage. For simplification, this study assumes that participants are striving for a major market position in each case and that success requires mastery of a complex technology. For each quadrant, freedom to operate is essential and must be achieved by not using the patents of others or licensing patents. In Quadrant I, since patents are crowded, not using the patents of others is difficult. However, the high rate of change offers good opportunities for inventions and improvements. These inventions and improvements can then be an asset for bartering or cross-licensing. In Quadrant II, when R&D staff have been fortunate to design a key invention. Companies focus must be to cover that invention both broadly and deeply as a new technology can generate considerable profit for many years when properly protected. Companies may end up with hundreds of cases in a key capability area. Although Quadrant III is crowded with patents, change is slow. Thus, the industry may be highly competitive with low profitability. Mastering a technology may be necessary for

Table 4 – Related fuel cell product applications.

	Application	Output	2009 Market	Technology
Transport	Buses	50–100 kW	150 Units	PEMFC
	Vehicles	50–80 kW	1150 Units	PEMFC
	Niche Transport	1–10 kW	15,000 Units	PEMFC DMFC
Stationary	Small Stationary • Residential CHP • Commercial CHP • DG power plants • Industrial/military • Farm/agriculture applications • UPS	<10 kW	20,000 Units	PEMFC SOFC
	Large stationary • Hotels and Holiday centers • Data centers, hospitals and other premium power • Grid support and grid-off operations	10–20 kW 200–300 kW >1 MW	1050 Units	MCFC SOFC PEMFC
Portable	3C products • Notebook PCs • PDAs, MP3/4 players & other electronics • Military communication • Military equipment • Portable generators & chargers	< 100W	35,000 Units	DMFC PEMFC

Source: RNCOS [44]; Madsen and Andersen [45].

Table 5 – Commercially available PEMFC products.

Manufacturer	Product Name	Application	Output
Ballard	FCVelo City 9SSL	Materials Handling Forklifts Classes I, II, and III	4.4–19.3 kW
	FCGen 1030	Residential Cogeneration	1.2 kW
	FCGen 1020A CS	Back-up power	0.3–3.4 kW
	FCVelo City	Bus and Heavy Duty Trucks	75 and 150 kW
ClearEdge Power	CE5	Residential CHP	500 W
Horizon	H-100	Uninterrupted Power Supply	100 W
	H-1000	Uninterrupted Power Supply	1 kW
	H-3000	Uninterrupted Power Supply	3 kW
	GreenHub	Uninterrupted Power Supply	500 w–2 kW
	MiniPak	Portable Battery Charger	100 W
Hydrogenics	HyPM XR Power Modules	Stationary	4, 8, 12 kW
	HyPM Rack	Stationary	Multiples of 10, 20, 30 kW
	FCXR System	Stationary	150 kW
	HyPM HD Power Modules	Mobility	4, 8, 12, 16 kW
	HyPX Power Packs	Class 1 Forklift Trucks	8–12 kW
IdaTech	ElectraGen™ 3	Backup Power for Telecom	3 kW
	ElectraGen™ 5	Backup Power for Telecom	5 kW
	ElectraGen™ H2-1	Backup Power for Telecom	2.5–5 kW
	iGen™	Portable, Backup Power for Telecom	250 W
	ElectraGen™ ME	Backup Power for Telecom	2.5–5 kW
Morphic Technologies	Mira 6	Boats, Forklifts, APU	6 kW
	Max-E 3600	Battery Charger for RV	150 w
	Polaris TLC	Backup Power for Telecom	5 kW
	Polaris 5	APU	5 kW
	Orion 5	APU	5 kW
	Orion 1	Residential CHP	Unknown
Nuvera	PowerEdge CS25, CM25, CM32, RL25	Counterbalance Lift Trucks and Reach Trucks	25–31 kW
	PowerFlow PFC-5	Industrial Vehicles	5 kW
	Andromeda Fuel Cell Stack	Transportation	100 kW
	HDL-82 Power Module	Transportation	82 kW
Plug Power	GenDrive 160	Materials Handling Vehicles	8.7 kW
	GenDrive 170	Materials Handling Vehicles	10.1 kW
	GenDrive 240	Materials Handling Vehicles	10.5 kW
	GenDrive 312	Materials Handling Vehicles	2.6 kW
	GenCore® 5T Series	Backup-Telecom	5 kW
	GenCore® 5U Series	Backup-Utilities	5 kW
	GenCore® 5B Series	Backup-UPS	5 kW
	GenSys 6U48	Residential CHP, Backup power	6 kW
Protonex	M300-CX	Portable Battery Charger	300 W
	UAV-C250	UAV Power Source	250 W
	UGV-C250	UGV Power Source	250 W
Relion	T-1000	Backup	600–1200 W
	T-2000	Backup	600 W–2 kW
	I-1000	Backup	1 kW
Trulite	KH4 Power System	Portable	150–250 W
UTC Power	PureMotion® 120 System	Transportation	120 kW
	PureCell® System Model 5	Backup	5 kW

Source: NREL [46].

entry, but is likely not a source of competitive advantage. This quadrant is defined by mature industry; however, mature industries can become subject to change from new environmental factors. Quadrant III businesses can move to Quadrant I. Notably, Quadrant IV is difficult to characterize. One must understand the reasons for few patents. Is a technology old and have the patents expired? Does a technology flow in from outside the industry? If so, there may be an opportunity to change the habits of the industry and gain great advantage by patenting industry-specific embodiments of the technology that is flowing in, e.g., patent microprocessor control for making bricks. Perhaps an industrial scene is static no opportunities exist. This would be surprising for technology-dependent fields. Therefore, the job of an R&D or technology manager is not done without the right patent strategy, effective and improving patent systems and the right patents. This area is becoming more and more important. In many cases, mediocre technical work but outstanding patent strategy can win against excellent science but poor patent strategy, and no situation will be more frustrating to the technology team.

Continuously, we would elaborate “logistic growth curve” which was the most popular growth curve model in

Table 6 – Commercially available SOFC products.

Manufacturer	Product Name	Application	Output
Ceramic Fuel Cells Limited	Gennex	Micro-CHP	1 kW
	BlueGen	Small Scale Electricity Generation	2 kW
Protonex	M300-CX	Portable Battery Charger	300 W
	UAV-C250	UAV Power Source	250 W
	UGV-C250	UGV Power Source	250 W

Source: NREL [46].

technology forecasting field. The concept of logistic growth curve was proposed by Velhurst [32], where two fundamental hypotheses are used to derive the curve's formulation, viz. 1. The rate of reproduction is proportional to the existing population, and 2. The rate of reproduction is proportional to the amount of available resources. The same hypotheses also represent the basis of two later contributes, i.e. Lotka [33] and Zwanzig [34]. The logistic growth curve model requires particular information about the technology performance level already achieved and the distance to the upper limit [26,28]. The model of Logistic growth curve or simply the well known S-curve is described by the following equation [14,15,32,35]:

$$P(t) = \frac{k}{1 + e^{-\frac{\ln(81)}{dt}(t - t_m)}} \tag{1}$$

where:

$P(t)$, The population over time

k, The capacity of the population, showing how large the population P will become.

dt, the characteristic duration of the curve, *i.e.*, the time needed for P to grow from 10% to 90% of k.

t_m, The midpoint of the curve at which 50% of k is reached.

Using Loglet Lab software, which can fit growth processes using one or more s-curves and a possible initial displacement, a logistic fit is produced that is tested against actual world data and utilized to make projections about the global economy.

3. Survey design and data sources

As this study investigates the technology forecasting of hydrogen energy and fuel cell. Study data were collected from the online USPTO database [36], which was first built in 1969. The data collected covered the period of 1969 to the 2008. This study first determined data frequencies using Bibliometric. Data were then input into Loglet Lab software to generate logistic growth curves. Finally, this study obtained technology growth curve data for the saturation, midpoint, and growth of time for analyzing technology developments and tendencies. Additionally, Co-word analysis is the most common analytical tool for inferring a cognitive structure from words appearing together and extracting multiword phrases or keywords frequencies [17]. Therefore, this study used Co-word analysis to infer the cognitive structure of words appearing together and extracting multiword phrases or keywords frequencies based on an expert survey [25]. The cumulate frequencies of data for fitting logistic growth curves can be used to determine the technological performance of hydrogen energy and fuel cells.

The logistic growth curve in this study was programmed into Loglet Lab software. The software calculated time-series growth datasets to acquire growth curve information about saturation (it describes the saturation level of the logistic curve), midpoint (or turning point; it describes the midpoint of the logistic curve, at which the logistic curve begins to level off), and growth time (it describes the time in which a logistic curve increases from 10% to 90% of its expected saturation level or the growth and mature stage of a technology's lifecycle).

4. Empirical results

Using Loglet Lab software and patent publications data, logistic fits are produced for hydrogen energy and fuel cell technologies. Table 1 lists the analytical results of each fit. Figs. 6–10 present growth curves based on actual data and fitted models for the period 1969–2008 (as of December of each year).

In the growth curve model, determining fit precision is very important. By applying a technique called parametric bootstrapping (i.e. the bootstrap method), one can compute a confidence interval for each parameter. The bootstrap method is a means of re-creating and re-sampling data using Monte Carlo methods [37,38]. The bootstrap method synthesizes a dataset by

Table 7 – Commercially available DMFC/DAFC products.

Manufacturer	Product Name	Application	Output
Oorja Protonics	OorjaPac	Materials Handling Vehicles	Unknown
SFC Smart Fuel Cell	EFOY Series 600, 900, 1200, 1600, 2200	APU for mobile homes, power for leisure markets	25, 38, 50, 65, 90 W
	EFOY Series 600, 900, 1200, 1600, 2200	Portable, Backup Power for security markets	25–90 W

Source: NREL [46].

re-sampling residuals from an initial fit, and fitting a curve to the new dataset. The Central Limit Theorem assumes that bootstrapped parameter estimates are normally distributed around a sample mean. From these sets one can compute confidence intervals for parameters. Loglet Lab repeats this process of synthesizing and refitting 200 times, producing a sample dataset of 200 values for each parameter, from which their respective confidence intervals are computed. From the confidence intervals of a parameter, it would forms a confidence region containing the set of all curves corresponding to all values of a given parameter. The growth curve analysis based on published patent would take some analysis error. Therefore, the bootstrap method was also adopted to estimate a confidence interval for the growth curve and cover the estimate error from the global crisis.

Traditionally, bootstrap confidence intervals have been determined using various methods [37], such as the standard bootstrap method, percentile bootstrap method, and biased-corrected percentile bootstrap method. This study applied percentile bootstrap analysis to establish bootstrap confidence intervals. Take the example of “hydrogen generation technology”. The shadow area in Fig. 6 represents 90% bootstrap confidence intervals on estimated parameters for growth of “hydrogen generation technology”. The intervals of estimated parameters were then obtained; the “saturation” number was 1445.4–2510.9, the “midpoint” was 2006.7–2016.6, and “growth time” was 28.8–42.3 years. Table 2 also summarizes sensitivity analysis results for other cases. Congruence analysis results indicate that the estimated growth curve and bootstrap confidence intervals of each technology minimize forecasting error and achieve a highly accurate forecasting power.

In addition, investigating the development activities of hydrogen generation technologies, the numbers of publications of those technologies were obtained from the USPTO database for the period 1969–2008 year. Using the keywords “hydrogen production” and “production of hydrogen” in the title (TTL), abstract (ABST), and claims (ACLM) yielded 1448 publications for this period. The cumulative publications data for hydrogen generation technologies were modeled using the logistic growth curve function, and significant information about the technological lifecycle of hydrogen generation was then obtained (Table 3). The midpoint of the hydrogen generation growth curve was at the year 2012, the duration of growth time was 36.6 years; the drop in publication activity in 2012 may also indicate that the technology growth curve passes an inflection point. For the periods 1994–2012 and 2012–2030, the growth curve was divided into growth and mature stages. The saturation number of publications of the cumulative hydrogen generation might be attained to 1972.0. Restated, the growth stages of hydrogen generation were estimated as follows: the “emerging state” was 1969–1994; the “growth state” was 1994–2012, the “mature state” was 2012–2030, and the “saturation period” was 2030.

5. Conclusions

5.1. *Discussion*

New clean energies have been recognized as drivers of today’s rapidly changing environments. Hydrogen energies now play important roles in the new clean energies field. However, few studies have forecasted new clean energies development. This study applied the Logistic growth curve model to investigate the technological performance of hydrogen energy, which includes its generation and storage, and the PEMFC, SOFC, and DMFC/DAFC. This study also presents patent strategies for the fuel cell industry. Empirical analyses are based on an expert survey and Co-word analysis of the USPTO database to obtain useful data. This study is an important reference for technology forecasting and development of the new clean energies field.

Simulation results indicate that hydrogen production and hydrogen storage technologies are still currently in their growth stage. This is primarily because hydrogen production technologies are analyzed in terms of water decomposition, light decomposition, and the reforming reaction, with an enormous number of patents for myriad technologies. This means that a patent search would generate both well-developed and new hydrogen production technologies. Hydrogen storage technologies have not reached the mature stage and are developing at a slower pace than generation technologies. This is mainly because the requirements for hydrogen storage systems are stringent and current development has hit a bottleneck. Notably, analytical results indicate that hydrogen storage technologies are in the growth stage. In summary, the timelines for hydrogen production and storage technologies will be a long before reaching the mature stage.

Hydrogen storage technologies must satisfy several requirements simultaneously, including the infrastructure, cost, and charging capabilities. Hydrogen storage technologies are considered from the energy production to the end usage. Specific barriers include safety, performance (e.g., charge/discharge, weight volume), cost, technical adaptation for the infrastructure, and scalability (e.g., applicable to small and large vehicles) [39]. Achieving a significant penetration of hydrogen into future energy systems depends on the ability to significantly improve hydrogen production, distribution, storage and utilization methods beyond their current performance, reliability and cost [7]. Ongoing research projects involving a hydrogen storage system include the U.S. DOE National Hydrogen Storage Project [40,41], PV-Wind-hybrid systems project [42], and UNIDO-ICHET project [43]. The major scientific and technical challenges for the hydrogen economy are summarized below:

(1) Lowering the cost efficiency of hydrogen production to a level comparable to the energy cost of petrol,
(2) Developing a CO_2-free route to mass produce sustainable hydrogen at a competitive cost,
(3) Developing a safe and efficient national infrastructure for hydrogen delivery and distribution,
(4) Developing viable hydrogen storage systems for both vehicular and stationary applications and
(5) Significantly reducing costs and significantly improvement in the durability of fuel cell systems.

Fuel cell technology is either in the mature stage or approaching maturity. However, fuel cell technology is still constrained by challenges associated with hydrogen storage and production. The commercialization of fuel cell vehicles and communication, computer, and consumer (3C) products will likely be delayed due to problems related to hydrogen production and storage. In addition to technological barriers, issues of product substitution and high price are additional obstacles. Thus, hydrogen energy products will likely not be commercialized until 2030 or later. Table 4 summarizes the current related fuel cell related product applications.

5.2. *Development strategies*

5.2.1. *PEMFC*

The PEMFC technology, which is the mature stage, is characterized by R&D personnel with adequate experience and knowledge, a high level of commercialization, and products available for customers. In this mature stage, firms achieve high margins when embarking on technological upgrades in response to customer demands. Thus, technologies in this stage are mainstream technologies, and firms should dedicate additional resources to their improvement and thereby cut costs. One feature of the mature stage is that crowding in the patent contest and field evolvement tend to slow. Thus, according to the patent strategy matrix, a firm should adopt the design-around strategy, generate niche inventions, and license patents. Technological maturity in this study refers to the wide application of related technologies and many related products on the market, such as fuel cell cars, back-up power, and 3C products. PEMFC technology represents the mature stage from a macroscopic perspective. Unfortunately, not all PEMFC technologies have reached maturity. Most commercially available hydrogen energy products are substitute products. Additionally, when technology is mature, industry is in a market in which market status of leading technology products is gradually secured. In the case of the PEMFC, development is targeted to stationary systems and fuel cell cars. Newcomers to this industry would manufacture those two mainstream products, while manufacturers of non-mainstream products would only strive to survive in very few niche markets. With well-defined product demands in the mature stage, the focus of development should be on how to undertake rapid market expansion, market products to consumers, and improve production efficiency to reduce costs and product prices. Table 5 present the current commercially available PEMFC products.

5.2.2. *SOFC*

The SOFC technology has just reached the mature stage, such that a firm's investment in technological upgrades in response to customer demands will achieve a high margin. Technology in this stage is mainstream technology and firms should strive to improve existing technologies to reduce costs. At the same time, the patent strategy should stress licensing and improvements to technologies. The SOFC industry is currently the market growth stage. However, as SOFC technology will have significantly longer timeline than PEMFC to transform from the mature stage to the saturation stage, markets will take a long time to develop before steady expansion, despite the fact that directions for leading technology products have been generally identified. Table 6 present the current commercially available SOFC products.

5.2.3. *DMFC/DAFC*

The DMFC/DAFC technology will soon enter its mature stage. Leading technology products in the direction of portable devices are gradually emerging. Although DMFC/DAFC technology is still in its growth stage, its applications are already extensive, particularly in military applications. Thus, firms should endeavor in improve existing technology to cut costs and adopt design-around strategies, niche inventions strategies, licensing strategies for development around patents. Table 7 present the current commercially available DMFC/DAFC products.

5.3. *Conclusions*

The three fuel cells—PEMFCs, SOFCs, and DMFCs/DAFCs—do not have entirely identical applications and their commercialization timelines differ. While all these technologies are mature, product maturity and total marketization are still a long way off in the future. Thus, in terms of market competitiveness, firms should adopt approaches for selecting key technologies, reducing costs, seeking licensing, and technological improvements, while stressing designing around patents. Overall, as the technologies of the three fuel cells are mature, the basic patent strategy matrix should focus on licensing, designing around patents, and improved development. The basic patent strategy combined with patent matrix analysis results may help firms choose an appropriate patent strategy and make the best use of patents. However, as is well known, REs development is complex with many influential factors [47]. Therefore, despite its contributions, this study has certain limitations. Data for related parameters data of the applied methodology, as collected by government public data, may influence the reliability of such analyses. However, they are often beyond the control of the researcher's ability. The accuracy and reliability of the data used also affects the accuracy and application of the analyses performed in this study. Resolving the above limitations is a viable avenue for further research and model improvement.

Acknowledgment

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC97-3114-E011-001 and No. NSC98-3114-P-006-002.

REFERENCES

[1] Kothari R, Buddhi D, Sawhney RL. Comparison of environmental and economic aspects of various hydrogen production methods. Renew Sust Energ Rev 2008;12(2):553–63.
[2] Beccali M, Brunone S, Cellura M, Franzitta V. Energy economic and environmental analysis on RET-hydrogen systems in residential buildings. Renew Energ 2008;33(3):366–82.
[3] Gasafi E, Reinecke MY, Kruse A, Schebek L. Economic analysis of sewage sludge gasification in supercritical water for hydrogen production. Biomass Bioenerg 2008;32(12):1085–96.
[4] IEA. International Energy Agency (IEA), http://www.iea.org/; 2010 [accessed 31.12.10].
[5] Rogner HH. Hydrogen technologies and the technology learning curve. Int J Hydrog Energ 1998;23(9):833–40.
[6] Galvita V, Messerle VE, Ustimenko AB. Hydrogen production by coal plasma gasification for fuel cell technology. Int J Hydrog Energ 2007;32(16):3899–906.

[7] Edwardsa PP, Kuznetsova VL, Davidb WIF, Brandon NP. Hydrogen and fuel cells: towards a sustainable energy future. Energ Policy 2008;36(12):4356–62.

[8] Dutton AG. Hydrogen energy technology. Tyndall Working Paper TWP17, Tyndall centre for climate change, http://www.tyndall.ac.uk/publications/working_papers/wp17.pdf; 2002 [accessed 31.12.08].

[9] IEA. International Energy Agency (IEA), Hydrogen production and storage: R&D priorities and gaps, http://www.iea.org/papers/2006/hydrogen.pdf; 2006 [accessed 31.12.10].

[10] Michael B, Martin W. The hydrogen economy: opportunities and challenges. New York: Cambridge University Press; 2009.

[11] Frank LD. An analysis of the effect of the economic situation on modeling and forecasting the diffusion of wireless communications in Finland. Technol Forecast Soc Chang 2004;71(4):391–403.

[12] Schilling MA, Esmundo M. Technology S-curves in renewable energy alternatives: analysis and implications for industry and government. Energ Policy 2009;37(5):1767–81.

[13] Chu WL, Wu FS, Kao KS, Yen DC. Diffusion of mobile telephony: an empirical study in Taiwan. Telecommun Policy 2009;33(9):506–20.

[14] Dergiades T, Dasilas A. Modelling and forecasting mobile telecommunication services: the case of Greece. Appl Econ Lett; 2010:1–6. doi:10.1080/13504850903373258.

[15] Lee M, Cho Y. The diffusion of mobile telecommunications services in Korea. Appl Econ Lett 2007;14(7):477–81.

[16] Norton MJ. Introductory concepts in information science. New Jersey: ASIS; 2001.

[17] Watts RJ, Porter AL. Innovation forecasting. Technol Forecast Soc Chang 1997;56(1):25–47.

[18] Garfield E. Citation data as science indicators. In: Elkana Y, Lederberg J, Merton RK, Thackray A, Zuckerman H, editors. Toward a metric of science: the advent of science indicators. New York: John Wiley & Sons Press; 1978.

[19] Narin F, Olivastro D, Stevens KA. Bibliometrics/theory, practice and problems. Eval Rev 1994;18(1):65–76.

[20] Morris S, DeYong C, Wu Z, Salman S, Yemenu D. DIVA: a visualization system for exploring document databases for technology forecasting. Comput Ind Eng 2002;43(4):841–62.

[21] Watts RJ, Porter AL. R&D cluster quality measures and technology maturity. Technol Forecast Soc Chang 2003;70(8):735–58.

[22] Martino JP. A review of selected recent advances in technological forecasting. Technol Forecast Soc Chang 2003;70(8):719–33.

[23] Bengisu M, Nekhili R. Forecasting emerging technologies with the aid of science and technology databases. Technol Forecast Soc Chang 2006;73(7):835–44.

[24] Cheng AC, Chen CY. The technology forecasting of new materials: the example of nanosized ceramic powders. Rom J Econ Forecast 2008;9(4):88–110.

[25] Chen YH, Chen CY, Lee SC. Technology forecasting of new clean energy – the example of hydrogen energy and fuel cell. Afr J Bus Manage 2010;4(7):1372–80.

[26] Porter AL, Roper AT, Mason TW, Rossini FA, Banks J. Forecasting and management of technology. New York: Wiley; 1991.

[27] Bhargava SC. A generalized form of the fisher-pry model of technological substitution. Technol Forecast Soc Chang 1995;49(1):27–33.

[28] Meade N, Islam T. Technological forecasting—model selection, model stability, and combining models. Manage Sci 1998;44(8):1115–30.

[29] Beck J, Grajek M, Wey C. Estimating level effects in diffusion of a new technology: barcode scanning at the checkout counter. Appl Econ; 2009:1–12. doi:10.1080/00036840802600624.

[30] Ernst H. The use of patent for technological forecasting: the diffusion of CNC-technology in the machine tool industry. Small Bus Econ 1997;9(4):361–81.

[31] Berkowitz L. Getting the most from your patents. Res Technol Manage 1993;36(2):26–31.

[32] Velhurst PF. Notice sur la loi que la population poursuit dans son accroissement. Corresp Math Phys 1838;10:113–21.

[33] Lotka AJ. Elements of physical biology. Baltimore (MD): Williams and Wilkins; 1925.

[34] Zwanzig R. Generalized verhulst laws for population growth. Proc Natl Acad Sci 1973;70(11):3048–51.

[35] Meyer PS, Yung JW, Ausubel JH. A primer on logistic growth and substitution: the mathematics of the loglet lab software. Technol Forecast Soc Chang 1999;61(3):247–71.

[36] USPTO. United states patent and trademark office (USPTO), http://www.uspto.gov/; 2009 [accessed 31.12.08].

[37] Efron B. Bootstrap methods: another look at the jackknife. Ann Stat 1979;7(1):1–26.

[38] Efron B, Tibshirani RJ. An introduction to the bootstrap. New York: Chapman and Hall; 1993.

[39] Mori D, Hirose K. Recent challenges of hydrogen storage technologies for fuel cell vehicles. Int J Hydrog Energy 2009;34(10):4569–74.

[40] Satyapal S, Petrovic J, Read C, Thomas G, Ordaz G, The US. Department of Energy's National Hydrogen Storage Project: progress towards meeting hydrogen-powered vehicle requirements. Catal Today 2007;120(3–4):246–56.

[41] Venetsanos AG, Adams P, Azkarate I, Bengaouer A, Brett L, Carcassi MN, et al. On the use of hydrogen in confined spaces: results from the internal project InsHyde. Int J Hydrog Energ 2011;36(3):2693–9.

[42] Panahandeh B, Bard J, Outzourhit A, Zejli D. Simulation of PV–Wind-hybrid systems combined with hydrogen storage for rural electrification. Int J Hydrog Energy 2011;36(6):4185–97.

[43] Suha Yazici M. UNIDO-ICHET support to hydrogen and fuel cell technologies in Turkey. Int J Hydrog Energy; 2010. doi:10.1016/j.ijhydene.2010.11.120.

[44] RNCOS. Fuel cell industry analysis. RNCOS E-Services Pvt. Ltd.; 2009.

[45] Madsen AN, Andersen PD. Innovative regions and industrial clusters in hydrogen and fuel cell technology. Energ Policy 2010;38(10):5372–81.

[46] NREL. National Renewable Energy Laboratory (NREL). 2009 fuel cell market report, https://www1.eere.energy.gov/informationcenter/; 2010 [accessed 31.12.10].

[47] Lee SC, Shih LH. Renewable energy policy evaluation using real option model – the case of Taiwan. Energy Econ 2010;32(Suppl. 1):S67–78.