The emergence of fuel cell technology and challenges to latecomer countries:
Insights from Singapore and Malaysia

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This article uses the systems of innovation approach (in this case using the technological system framework and analysis of system functions) to provide insights for understanding the challenges that latecomer countries have to face in the development of an emerging technology like fuel cells. It shows that the development of system functions in fuel cells in Singapore is higher than in Malaysia, and this is shaped by four key factors: (1) Diversity of actors and the alignment of their activities; (2) synergy between energy, environment and industrial policies; (3) openness to internationalisation; and (4) responsiveness to demonstration activities. In Singapore the stronger presence of such factors in its policy environment has had a positive influence on the development of fuel cell technology – while the absence or weaknesses of these factors might have contributed to the weaker and more unbalanced development in Malaysia. It is argued that this is because such factors were effective in addressing specific characteristics of the 'emerging phase' of fuel cell technology.

KEYWORDS: latecomer countries, catching-up strategy, fuel cells, emerging technology, innovation system, functional analysis

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1. Introduction

Fuel cell technology is popularly considered as an enabling technology to achieve the so called greener, more sustainable and low-carbon vision of the future due to its increased image as an environmentally friendly and efficient system for the production of electricity (Cacciola et al., 2001: 67). Arguments on the environmental advantages of this technology are abundant, and this includes the advantages to mitigate problems associated with air pollution, climate change and depletion of fossil fuel. Also rapid progress in fuel cell technology, its impact for future economic, environmental and social issues and the increasing involvement of various actors and countries in its development (OECD, 2006), are clear signals for its possible impact in worldwide technological development and industrial transformation.

However, there are also concerns expressed by some development analysts on the potential impact of fuel cell technology to increase the technology gap between the advanced and less-advanced countries (Mytelka, 2003; Mytelka and Boyle, 2006; ICCEPT, 2002). They call for a clear need to understand how less-advanced or latecomer countries can be included in the development of this technology without widening inequalities in reaping the environmental, social and economic benefits of technical change. This can be essential since technology transfer in low-carbon technology from the advanced to the less-advanced countries is increasingly becoming an important and difficult issue to deal with, especially within the context of climate change negotiations. This was clearly observed when the development and technology transfer of low-carbon technologies became a very important topic in the recent United Nations Framework Convention on Climate Change meeting in Bali (UNFCCC, 2007a) and the influential UK government's Stern Review on the Economics of Climate Change (UK HM Treasury, 2006: 516).

For this reasons, fuel cell technology provides a fresh and interesting case for addressing the objective of this paper, which is to understand the challenges for less-advanced or latecomer[1] countries to enter early in the development of new technologies, within the context of modern concerns for climate change, sustainable development and contemporary technological change[2]. The paper is divided into six sections. After this introduction, section two describes the characteristics of the emerging phase of fuel cell technology, followed by section three, which describes the methodology that has been used by the author to analyse the challenges for latecomer countries to participate in the development of this technology. Section four is the most important part of the paper, where the specific analysis on the development of fuel cell technology in Malaysia and Singapore is used as the empirical contexts to identify the factors

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[1]In this article, latecomer or less advanced countries refers to those countries that arrive late on the industrial scene. In this thesis, it is interested in latecomer countries from the mid 20th century that has less developed industrial infrastructure than the early-industrialized countries.

[2] Nevertheless, it is important to note that fuel cell technology was chosen as the subject for this article on the basis of it being a feasible and comparable empirical context for the research. The author of this article does not stand on a particular belief on the expected success or overall environmental merits of fuel cell technology, and does not seek to evaluate the prospects for developing fuel cell technology in the countries studied. How successful the technology will be is highly uncertain, and could also differ based on a wide range of applications (Powell et al., 2004). In fact, this state of flux and uncertainty is precisely the key characteristic of any emerging technology, and thus becomes an unavoidable challenge for latecomer countries when using early participation in the development of an emerging technology like fuel cells as a part of their development strategy.

that may promote or hinder the development of fuel cell technology in latecomer countries, and how this is associated with the specific characteristics of fuel cell technology as an emerging technology. The paper will end with its overall discussion in section five and a short conclusion in section six.

2. Fuel Cells as an emerging technology

The emergence of new technologies are characterised in various ways in the literature on innovation theory. However, perspectives have changed over time. In the early years, the emergence of new technology focused on the radicalness of the process, and was characterised by new and revolutionary ideas, technical variation and intense competition between new players (Utterback, 1994 Anderson and Tushman, 1990). This was in line with the early Schumpeterian notion of creative destruction. However, from late 1980s, the systems perspective began to take shape. Thus, rather than being a destructive and discontinuous process, the emergence of new technologies was seen as more continuous, and characterised by the relationship with other technologies and speciation from older technologies (Perez, 1988; Freeman and Perez, 1988; Adner and Levinthal, 2002; Bergek and Jacobsson, 2004). Finally, the increased environmental and global consciousness of the late 20th century has led to the development of the socio-technical perspective, which explicitly recognises the co-evolution of new technologies and the wider socio-technical environment (Kemp et al., 1998; Geels, 2004; Berkhout et al., 2004).

The literature also demonstrates that the characteristics of emerging technologies are not static. As argued by Mytelka (2003, 2004), the new technologies of the 21st century (or what she terms the 'new wave technologies') have features that are unique compared to emerging technologies of the past. Taking empirical examples from the development of biotechnology and fuel cell technology, Mytelka (2004) identifies three distinguishing features:

- Broad science knowledge base: new wave technologies are anchored by a scientific base Challenges to latecomers: Insights from the experience of
- Intensity of appropriation: new wave technologies have relatively high R&D costs which are usually amortised through patenting
- Systems embeddedness: new wave technologies require high levels of system integration with different types of technologies.

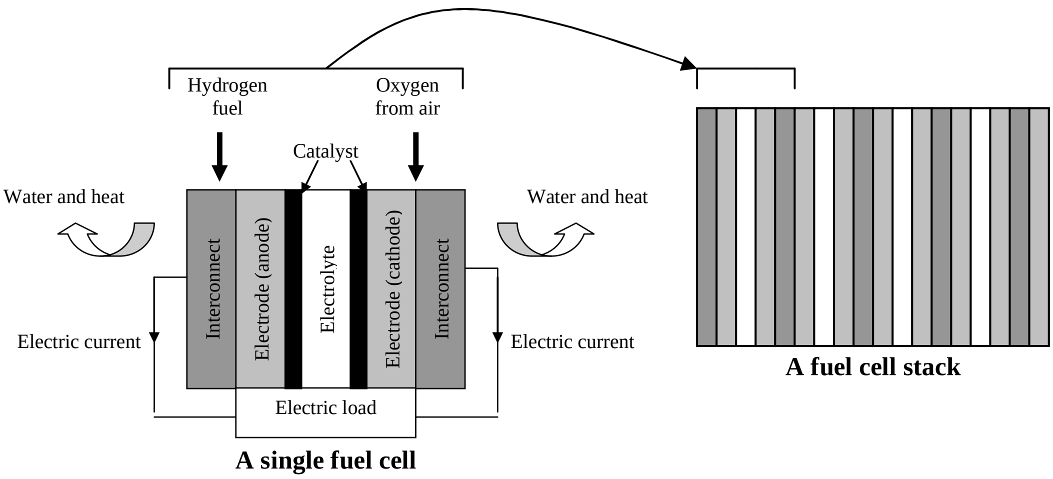
Therefore the conditions that Germany and United States had to deal with to catch-up with the United Kingdom during the 19th century in entering into the development of the chemical and steel industries (Freeman and Soete, 2000: 85, 55) may be very different from what current latecomer countries have to deal with when entering into emerging technologies of the 21st century.

This section describes such how these new and specific conditions characterises the development of fuel cells as a type of emerging technology. We begin by understanding fuel cells as a complex technical system (Section 3.1) before proceeding to the specific characteristics of its emerging phase (Section 3.2) and the entry of latecomers during this phase (Section 3.3).

2.1 Fuel cells a complex technical system

Fuel cell technology[3] is based on the electrochemical[4] process in which hydrogen and oxygen are combined to produce electricity, heat and water. The core of this technology is a single cell that consists of two electrodes (anode and cathode)[5] and an electrolyte,[6] sandwiched between two interconnectors.[7] Low-temperature fuel cells tend to require a noble metal catalyst,[8] typically platinum, to encourage the electrode reactions. Fuel cells has been claimed to represent a relatively cleaner technology for the production of electricity in which the only emission at the point of use is water (Larminie and Dicks, 2003: 3). A typical fuel cell is not a single cell but is a 'stack' of fuel cell units. The number of units in the stack determines total voltage, and the surface area of each cell determines total current. Total electrical power generated is the product of multiplying the voltage by the current. A fuel cell stack can be built, module by module, and scaled to suit any power requirements (see Figure 1).

Figure 1: Fuel cell technology: A single fuel cell and construction of a fuel cell stack



Source:
Adapted from diagrams in Larminie and Dicks, 2003: 3; Brett, 2005; Fuel Cell Today 2004a

As shown in Table 1, several types of fuel cell technology are currently being developed and at the moment they are mainly classified according to the types of electrolytes, and grouped according to their operating temperature. The low temperature group includes proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFC), alkaline fuel cells (AFC) and phosphoric acid fuel cells (PAFC). The high temperature group includes molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), which operate at temperatures of over 600°C. High temperature fuel cells do not require catalysts.

[3] Biological fuel cells and metal fuel cells can also be considered as fuel cells, but not within the definition used here.
[4] A branch of chemistry concerned with the relationship between electrical and chemical phenomena.
[5] The anode is the terminal point of the fuel cell where electric current enters, the cathode is the terminal point where electric current leaves. Collectively, they are referred to as an electrode.
[6] Electrolyte is a material that contains ions. In a fuel cell, the electrolyte is the material that allows electricity to flow from anode to cathode.
[7] In PEMFC, DMFC and PAFC the interconnector are also called flow field plates or bipolar plates.
[8] A catalyst is a substance that increases the rate of a chemical reaction, but is left unchanged by the reaction.

Table 1: Features of six main types of fuel cells

	Low Temperature Fuel cells (requiring catalyst)				High Temperature Fuel cells (not requiring catalyst)	
	AFC	**DMFC**	**PEMFC**	**PAFC**	**SOFC**	**MCFC**
Electrolyte	Potassium Hydroxide	Polymer membrane	Ion exchange polymer membrane	Phosphoric acid	Ceramic	Molten Carbonate
Operating temperature	60-90ºC	60-130°C	60-90°C	190-210°C	800 - 1000°C	650ºC
Power range	Up to 20 kW	< 10 kW	Up to 250 kW	> 50 kW	> 200 kW	> 1 MW

Source: Adapted from Fuel Cell Today, 2004b

The core and most novel part of a fuel cell technology is the fuel cell stack, but the stack needs to be supported by other technologies, collectively referred to as the balance of system or BOS. The BOS includes the fuel system, fuel delivery system, air system, cooling system, humidification system, electrical system, hydraulic system, control system, etc. The combination of fuel cell stack and BOS comprises the entire 'fuel cell technology'. The extent to which the BOS is required, may change for different types of fuel cells and their eventual application. The BOS frequently constitutes a large proportion of the engineering within a fuel cell system (Larminie and Dicks, 2003:19-21). However, a fully operational fuel cell technology includes the fuel cell stack and the BOS, and also its connection to its final application and hydrogen source. As an energy conversion technology, fuel cell technology is demonstrating increasing potential for providing cleaner and quieter means of producing electricity for a broad range of applications. There are currently three main commercial areas for the application of fuel cells, namely, for stationary power,[9] for transport,[10] and for portable equipment.[11] Applications for the space and military sector represent much smaller and very specialised markets (Fuel Cell Today, 2004c).

Despite promising advances in fuel cell stacks, BOS and applications, the hydrogen source remains a major barrier to the deployment of fuel cell technology worldwide. Pilkington (2004: 763) points out that there are no infrastructures capable of supporting the supply of hydrogen required for the mass introduction of fuel cells. Most of the actors involved in developing the technology, however, are sourcing hydrogen by reforming hydrogen rich fossil fuels, such as gasoline and natural gas (Fuel Cell Today 2004d). By retaining dependence on fossil fuel, this 'reforming technology' has the advantage of sourcing hydrogen without the need to radically transform existing infrastructures and industrial networks. It has been argued that this provides little or no benefit in terms of emissions reductions and may result in lock-in to an inferior

[9] This includes power for residential and non-residential applications (such as schools, office blocks, banking facilities, factories) for different power ranges from small (1-10kW), medium (10-300kW) and large (250kW-10MW) (Cacciola, 2001: 68).
[10] This includes cars, buses, trains and various niche vehicles (e.g. aircraft, scooters, forklifts, motorcycles, wheelchairs, human transporters)
[11] Fuel cell technology is seen as an important source for mobile electronic devices. It has several advantages over conventional batteries, such as increased operating times, reduced weight and ease of recharging (Fuel Today, 2004c)

technology, which could prevent a radical transition towards a low carbon economy (Hart, 2000). Nonetheless, there is active development oriented to producing more sustainable forms of hydrogen through electrolysis of water using renewable energy sources (such as solar, geothermal, biofuel and wind energy) and biological processes. Compared to the reform of fossil fuel, the development of more sustainable forms of hydrogen source are still at the experimental stage and prospects are uncertain.

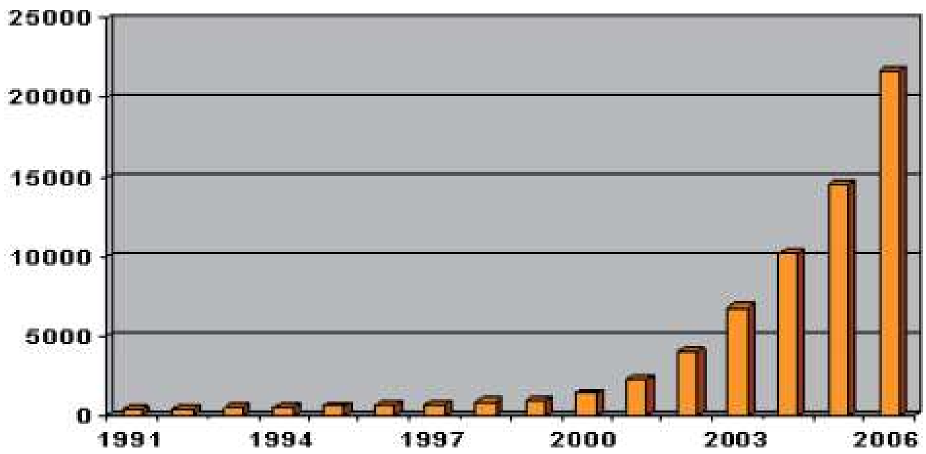
From this description, one could conclude that fuel cell technology is not a clear-cut emerging technology, especially when it is viewed within the perspective of a functional and workable technical system. It is very important to take note that the most novel parts of the fuel cell system is the fuel cell stacks and the use of pure hydrogen from sustainable sources. Other parts of the fuel cell system, such as the BOS, fuel cell applications and the use of hydrogen from fossil fuel, are relatively much more established, and innovation in these more established areas are closely associated to developments in the more novel parts of the technology. In this case, capabilities in system integration is very important for advancing this technology and, therefore, it is not surprising that its development is replete with partnerships between new and incumbent actors with combinations of different expertise, resources and experience – as will be highlighted in the next sub-section.

2.2 The emerging phase of fuel cell technology

The history of fuel cells goes back to 1839, when a British judge and scientist, Sir William Robert Grove, discovered he could generate electricity by combining oxygen and hydrogen. Grove built a device called a 'gas battery' using sulphuric acid as the electrolyte and platinum as the catalyst. His invention was enhanced 50 years later by the scientists Ludwig Mond and Charles Langer, when they used Grove's invention for the development of a practical device which they called a 'fuel cell'. Commercial development of Mond's and Langer's device was hindered by the exorbitant cost of platinum. In 1932 another British scientist, Francis Bacon, managed to construct a cell that used an alkaline electrolyte (now known as the AFC), which used nickel as the catalyst (Koppel, 1999: cited in Hall and Kerr, 2003: 464). Since then, several modifications have been made to these original inventions. This includes basic research fundamental to the design of various types of fuel cells currently being developed: SOFC, MCFC, DMFC, PAFC and PEMFC (Crawley, 2006a,b; 2007a,b,c).

However since its invention more than 100 years ago, fuel cells technology is still at the emerging phase of development as there continue to be deep uncertainties about whether it will gain wide-scale market acceptance (Hellman and Van den Hoed, 2007: 306). As Hart (2000: 2) points out: "The fuel cell is one of the oldest energy technologies known to man, yet its development has lagged behind that of its less elegant and often less efficient cousins, such as the internal combustion engine and the gas turbine". Currently, the fuel cell market is dominated by prototypes and demonstrations in niche applications, with the total number of installed fuel cell units reaching less than 25,000 in 2006 (Figure 2). For this reason, whether the technology will ever progress from this stage is still an open question. However, the fuel cell market has experienced an impressive growth rate since the end of the 1990s (Adamson and Crawley, 2007: 2).

Figure 2: Cumulative fuel cell units installed worldwide (1991-2006)



Source: Adamson and Crawley, 2007: 2

Fuel cell technology also experience fluctuating periods of success and failure throughout the history of its emergence. The clearest fluctuations include the shifting dominance from AFC/PEMFC and military/space applications in the early periods, to PAFC/MCFC and large stationary application in the middle period and finally to PEMFC/DMFC/SOFC and portable/medium-small stationary/transport application in the current period. Also during this long introduction phase, various activities by different types of actors have taken place. From the beginning of its development in the early advanced countries (particularly the US, UK, Germany and Japan), the technology has received high-level support from governments and involved early involvement of the private sector in R&D activities, particularly by large firms from well-entrenched industries. Therefore, much of the technology has been appropriated by large companies and public organisations in the early-industrialised world for over many years (Schaeffer, 1998)

Presently, development of the technology is characterised by intense research, development and demonstration activities, with only minimal success in commercialisation. This is because as a type of energy technology, the development of fuel cell technology is very costly and complicated due to the high level of system integration required. As a result, public-private partnerships have been used rather extensively as a mechanism to deal with this challenge. These partnerships have not been limited to the local or national level, but also occur extensively at the regional and international levels. This includes programmes such as the European Union (EU) framework Fuel Cell Programme, the PACo network in France, the Hydrogen and Fuel Cell Committee in Canada, the Freedom Car Programme in the US, the Transport Energy Strategy in Germany and various fuel cell specific projects in Japan[12] (OECD, 2006: 9, 100, 115-117, 266, 171-172).

[12] This includes the Project for Development of Platform Technologies for Highly Efficient Fuel Cell Systems and the Project for Development of Technologies for the Commercialisation of Highly Efficient Fuel Cell Systems within the Japanese government's 2000 Millennium Project.

Finally, fuel cell technology is highly influenced by three policy areas i.e. environmental policy, energy policy and industrial policy OECD (2006: 17-21). Environmental policy is associated with the global issue of climate change and transboundary air pollution, while energy policy is associated with dwindling sources of global sources of fossil fuel. At present, industrial policy, the third arena, is perceived as less of a global issue, but some policy makers are expressing their concerns about how the development of this technology will increase the industrial gap between the advanced countries and the rest of the world (Mytelka and Boyle, 2006). Hence, it has the potential to become politically more global.

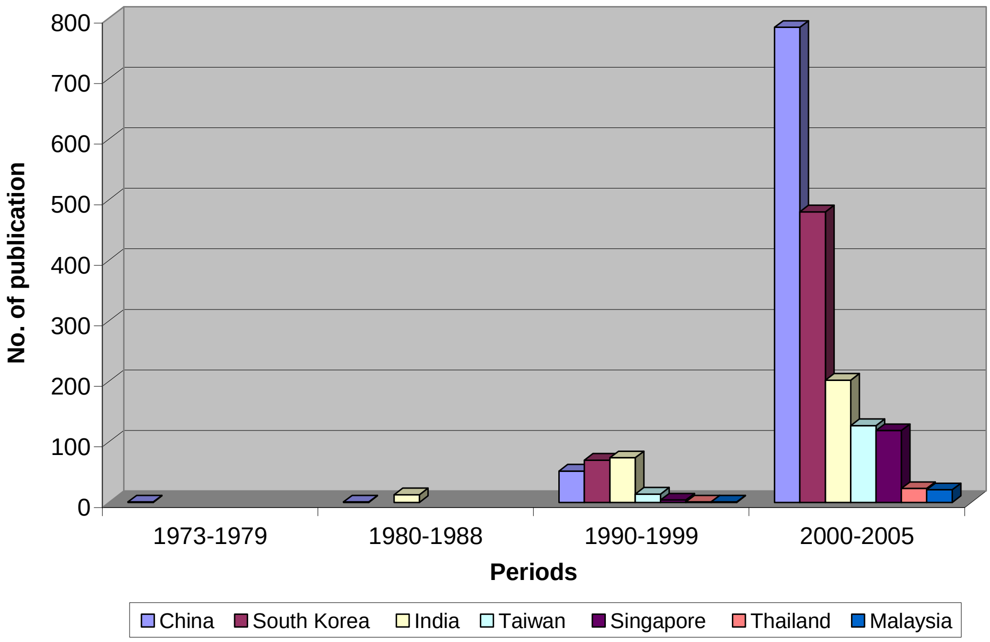
2.3 Participation by latecomers

Interest in the potential of fuel cell technology, particularly during this later stage of its emerging phase, is not only confined to the advanced countries (OECD, 2006); it is also attracting interest in some latecomer countries. This includes large countries with massive market potential such as Brazil, China and India, smaller countries such as Korea, Malaysia, Thailand and Taiwan, and even the small island nation of Singapore. However, the participation of other latecomer countries is less evident; in fact most latecomer countries, particularly those from most parts of the developing world, are still unprepared to deal with the rapid development of this technology (Mytelka and Boyle, 2006: 2). This has led to a concern that the development of fuel cell technology will create yet another area of inequality in terms of global technological development (Mytelka and Boyle, 2006: 8), where most developing countries will be merely passive users rather than active generators, producers and decision makers in this new emerging industry.

It is interesting that the latecomer countries that are actively involved in the development of fuel cell technology are also those that have undergone rapid industrialisation and economic growth in the past few decades. They are the types of countries that Perez and Soete (1988) describe as having achieved the ability to exploit windows of opportunity in new technologies due to decades of successful entry into mature technologies. This is in line with the findings in Albuquerque (1999). Based on statistical analysis of basic science and technology indicators, Albuquerque categorised these countries as catching-up national systems of innovation (referring to Korea, Taiwan and Singapore) or non-mature national systems of innovation (referring to Brazil, India, Malaysia, Thailand and South Africa). This categorisation clearly differentiates these countries from more backward countries where a national system of innovation is practically non-existent. The label national system of innovation refers to the presence of adequate actors, networks, institutions and infrastructures at the national level to enable innovative activity to take place.

There are clear indicators of the participation of this small group of latecomer countries in the scientific papers in the Institute for Scientific Information's Web of Science (ISI WoS) database. Analysis of these papers shows that the publication rates of some latecomer countries in the Asian region have increased rapidly since the 1990s (see Figure 3), with China, South Korea, India, Taiwan and Singapore ranked in order at the top of the list of the 20 countries with the highest number of publications in 2005 worldwide. In addition, organisations from China, Taiwan and South Korea have also shown impressive performance in patenting (Butler, 2007: 3) In addition, reports by Fuel Cell Today (Geiger, 2003a,b) and presentations at a international conference organised by UNU-MERIT on "Hydrogen Fuel Cells and Alternatives in the Transport Sector: Issues for Developing Countries" provide some evidence that countries like China (Pingwen, 2005), India (Chopra, 2005), South Africa (Mehlomakulu, 2005) and Malaysia (Wan Daud, 2005a) are involved in several activities related to the development of fuel cell technology. The Fuel Cell Today database also provides specific information on the involvement of various types of organisations within these countries working on various aspects of the technology.

Figure 3: Total publication in four periods by selected latecomer countries in Asia



Source: Author, based on ISI Web of Science data

However, systematic and comparable investigation into the development of fuel cell technology even in this relatively more advanced group of latecomers is lacking. The currently available information is only sufficient to indicate that there are some promising activities occurring in these countries, but it is difficult to ascertain to what extent their fuel cell innovation systems have been developed, and whether the progress they are making is comparable between themselves and with those in the advanced countries.

3. Methodology

The challenge of this article is to explore how specific characteristics of an emerging technology like fuel cells (as described in Sub-section 3.1 and 3.2) can affect the challenges and opportunities for latecomer countries (as described in Sub-section 3.3) to enter early into its development at the current period. In order to provide insights on this issue, this article employs the technological system framework and its functional analysis as its analytical tool to conduct an empirical investigation on the experience of two South-East Asian latecomer countries, Malaysia and Singapore, in their attempt to enter early in the development of fuel cell technology. Description of the analytical framework is described in Section 4.1 and the use of Malaysia and Singapore as the latecomer contexts is elaborated in Section 4.2.

3.1 Analytical framework: The technological system approach and its functional analysis

More than thirty years of empirical research has hardened the views of an increasing number of researchers in the science and technology policy field that innovation cannot be understood as an isolated phenomenon undertaken by a single actor, but is part of a larger 'system of innovation'. This system of innovation approach recognises that innovation as an economic activity does not only rely on firms' activities alone, but includes a network of actors in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies. In essence, it is a framework of innovation as an interactive process in which firms interacting with each other and supported by other types of organisations, play the key role in bringing new products, new processes and new forms of organisation to economic use (Freeman, 1987; Lundvall, 1992; Nelson, 1993).

Since the introduction of the popular national systems of innovation approach by Freeman, Lundvall and Nelson in the late 80s/early 90s, a number of systems of innovation frameworks or perspectives have emerged since, the main ones being the sectoral system of innovation (Breschi, and Malerba, 1997, Malerba, 2002, 2004), regional system of innovation framework (Cooke, 2004; Iammarino, 2005), the technological system framework (Carlsson and Stankiewicz, 1991; Carlsson et. al., 2002) and the socio-technical system framework (Kemp et al., 1998; Geels, 2002, 2004; Berkhout et. al, 2004). Their differences lie in their empirical boundaries, and how these boundaries affect the ways in which their empirical investigation has been undertaken. Methodologically, these different system of innovation frameworks are necessary in dealing with the inherent difficulties involved in analysing the innovation system as a generic system, with its broad and multifaceted possibilities.

In the analysing issues related to the emergence of new technologies, the technological system[13] framework seems the most relevant. A technological system can be defined as:

> network(s) of agents interacting in the economic/industrial area under a particular institutional infrastructure for the purpose of generating, diffusing and utilising technology. (Carlsson and Stankiewicz, 1991: 94)

Why is this? There are several reasons. One, a technological system is not necessarily confined to domestic and regional entities, but may be a part of larger international system; two, the characteristics of a technological system may vary considerably among various areas of technology. These characteristics of the technological system take into consideration the high level of internationalisation in current development of emerging technologies while recognising the specific characteristics of individual technologies (as described in earlier in Section 2). In addition, the technological system framework has been employed much more frequently to investigate the emerging phase of a technology's development and, as a result, this framework

[13] Some authors also use the term 'Technology specific innovation system' and 'Technological innovation system'

gives more emphasis to the dynamic nature of innovation system development compared to other innovation systems frameworks. As Jacobson (2002: 347) states:

> The (technological system) approach thus assumes that: the *emergence* [own emphasis] of new technologies, and the subsequent transformation of industry, does not take place in a vacuum but rather through a *dynamic* [own emphasis] interplay between firms and other organizations, such as universities, industrial associations and government bodies; and the nature of the institutional framework heavily influences the process.

This move within the technological system framework towards a more a dynamic analysis is understandable if we consider the volatile and unstable nature of emerging technology. Also, as Hekkert et al. (2007b, 417) mention, the technology-specific focus of the technological system framework reduces the number of actors, networks, and relevant institutions that need to be analysed, making dynamic analysis more feasible. Hence, this framework enables us to go beyond the more established practice of concentrating on the static analysis of current structures of innovation systems. Literature on socio-technical system also tend to concentrate on the development of emerging technologies – but since the literature is relatively new and has an extremely broad scope; its work is currently much more theoretical, and its analytical framework has less consensus between different authors.

In order to apply the technological system framework, it is important to appreciate its key elements. These elements have been characterised in various ways and new dimensions have been added over time. Initially, the framework was characterised solely by its three-pronged structural components: actors and their competences, networks, and institutions. However, in recent years, the framework has also included 'functions' as another key element of its analysis.

Functions constitute the intermediate level between the structural components and the performance of an innovation system. The idea is simply that the appropriate fulfillment of the functions by the structural components would contribute to the final aim of the technological system - which is the successful generation, adoption and diffusion of new technologies. Thus, function tackles the 'process' part of the framework, i.e. what the structural components actually do and eventually achieve. According to Jacobsson (2002: 348), there are two main reasons for analysing a technological system in functional terms:

> First, there is no reason to expect a particular configuration of a technological system, or structure, to be related to the performance of the system in a clear and unambiguous way. By arranging our empirical material in terms of functions, we can trace the way in which a particular entry/exit pattern, actor combination or a specific institutional set-up shapes the generation, diffusion and utilisation of new technology. Second, we can define the border of the system, an inherently very difficult task…by analysing what promotes or hinders the development of these functions.

Furthermore, the use of functions is considered particularly useful in the case of emerging technologies, where typical measures of economic performance are difficult due to their volatile and experimental nature. Initially, existing indicators[14] were recommended for analysing

[14] In their review of the technological system approach in 2002, Bo Carlsson and co-authors (p.243) adopted the approach suggested by Rickne (2001); which used a combination of conventional indicators (e.g. patent indicators, number of scientists

functions (Carlsson et al., 2002: 244); however, a 2001 paper by Anna Johnson had a significant influence on this issue. Johnson carefully identified a set of basic functions that are fulfilled in different types of research on innovation systems, i.e. national systems of innovation, technological system, the network approach and the development block approach. She identified eight types of basic functions involved in these different approaches. Based on Johnson's work, several listings of key functions of a technological system have been and continue to be developed by various scholars. To my knowledge, the most integrated and comprehensive attempt at defining and describing these functions was made in Bergek et al. in 2008,[15] which is an article recently published in Research Policy where several key scholars[16] have tried to consolidate their ideas. An adaptation of this list is provided in Table 2.

Table 2:
Summary of definition and suggested indicators of the functions of a technological system framework

Functions	Description	Suggested indicators
1. Knowledge development and diffusion	This function captures the breadth and depth of the knowledge base of the technological system, and how the knowledge is diffused and combined in the system	Publications, R&D projects: (number, size and orientation); patents: (number, orientation); assessment by actors (of types of knowledge, sources of knowledge and how knowledge has been used); assessment by managers.
2. Entrepreneurial Experimentation	A technological system evolves under uncertainties. The way to handle this uncertainty is to ensure that much entrepreneurial experimentation takes place. Some will fail and some will succeed, but an innovation system without vibrant entrepreneurial experimentation will stagnate.	Number of entrepreneurial experimentation (no. of entrants; diversification of established firms); variety of entrepreneurial experimentation; (no. of different applications, breadth of technologies used; character of complementary technology employed)
3. Direction of search	For a technological system to develop there must be sufficient incentives and/or pressure for a whole range of actors to enter into it. This function covers the mechanisms influencing the direction of search within the technological system.	Visions, expectations and belief in growth potential (e.g. incentives from factor/product prices, growth in other countries, changes in the policy landscape); actors perception of the relevance of different types and sources of knowledge; actor's assessment of technologies; opportunities; regulation and policy; articulation of demand from leading customers; technical bottleneck; crisis in current business.
4. Legitimation	Legitimacy is a matter of social acceptance and compliance with relevant institutions i.e. the new technology and its proponents need to be considered appropriate and desirable by relevant actors in order for resources to be	The strength of the legitimacy for the technological system; what (or who) influences legitimacy; how legitimacy influences demand, legislation and firm behaviour.

and engineers) and unconventional indicators (mobility of professionals; technological or scientific diversity; closeness to market exploitation through regulatory acceptance and number of partners).

[15] This is based on an earlier manual they presented in the DRUID Tenth Anniversary Summer Conference in 2005 (Bergek et al., 2005).

[16] This refers to Anna Bergek, Staffan Jacobsson, Bo Carlsson, Sven Lindmarki and Annika Rickne

	mobilised, for the demand to form and for actors in the technological system to acquire political strength.	
5. Market formation	For an emerging technological system, markets may be greatly underdeveloped or non-existent. Thus, three phases of market formation are required: nursing market (learning space is opened up, in which the technological system can find a place to be formed), bridging market (volumes start to increase and enlargement of technological system in terms of number of actors) and mass market (large and stable markets after several decades of market formation)	Market size; customer groups, actors' strategies, roles of standards, purchasing processes, lead users
6. Resource Mobilisation	As an innovation system evolve, a range of different resources needs to be mobilised. Key resources include finance, human capital and complementary assets.	Volume of capital; volume of venture capital; volume and quality of human resources; complementary assets
7. Development of Positive Externalities	As markets go beyond the first niche, there is an enlarged space in which the emerging system can evolve through different functions influencing and strengthening each other. Entry of firms is central to this process.	Political power; legitimacy; resolution of uncertainties; pooled labour market ; specialised intermediates; information and knowledge flows; combinatorial opportunities.

Source: Adapted from Bergek et al. (2008)

The investigation has used the analytical framework to compare the development of fuel cell technology within two Southeast Asian latecomer countries (Malaysia and Singapore) from the beginning of developments to February 2007, the end period of its research fieldwork. Insights gained from the empirical work on each of these two latecomer countries will then be compared with each other, particularly in identifying salient factors that has enabled or hindered the development of system functions of fuel cell technology in the respective countries. Type of data employed is mainly qualitative, with some support from quantitative data. Some international and historical dimension is included in the analyses to allow the findings (and ultimately its generalization) to be contextualized appropriately within the emergence of fuel cell technology worldwide.

3.2 Malaysia and Singapore latecomer contexts

Malaysia and Singapore have similar geographical, historical, cultural and economic contexts. Both countries are located in the equatorial belt of the South East Asian region and have similar climatic condition i.e. characterised by uniform temperature and pressure, high humidity and abundant rainfall. They also have some common neighbours, both being in close proximity to Indonesia, the Philippines, Brunei and Thailand. Singapore and Malaysia are open economies with high levels of foreign direct investment (FDI). Both countries are also known to be leading world production centres for electronic products and components.

Figure 4: Maps of Malaysia and Singapore

Source: CIA Worldfactbook[17]

Historically, their similarity goes back to the late 18th and 19th centuries. During this period, Britain established colonies and protectorates in the areas of current Malaysia and Singapore, known then as the ‘straits settlement’. After brief occupation by Japan from 1942 to 1945, the British-ruled territories on the Malay Peninsula in 1948 became the Federation of Malaya, which received independence in 1957. Malaysia was formed in 1963 when the former British colonies of Singapore and the East Malaysian states of Sabah and Sarawak on the northern coast of Borneo, joined the Federation. Two years later, Singapore separated from Malaysia and became independent through diplomatic means. However, there are distinct differences between the two countries. Singapore is a small and densely populated city state with a land area smaller than the smallest state in Malaysia. Other than fish and deep water ports, it has no significant natural resources. Malaysia, on the other hand, is endowed with abundant natural resources, including land, minerals (petroleum and natural gas) and agricultural produce. Singapore is significantly richer than Malaysia with a GDP per capita and internet users per capita nearly equivalent to the early-industrialised countries. In addition, Singapore’s energy consumption is among the highest in the world.

The economic development of both Malaysia and Singapore increased rapidly after independence (when they were considered third world countries), with an average annual growth rate of about 8% over recent decades (Koh and Wong, 2005: 15; Tidd and Brocklehurst, 1999: 10). However, Singapore has progressed much faster than Malaysia. By the end of the 20th century, Singapore was classified by various literatures as a first tier newly industrialising country alongside Taiwan, Hong Kong and South Korea, while Malaysia was classified alongside Thailand and Indonesia as a second tier industrialising country. By 2003, the World

[17] CIA Worldfactbook (2006) Malaysia. [Online] Available from: http://www.cia.gov/cia/publications/factbook/geos/my.html, accessed 20.05.06 and CIA Worldfactbook (2006)
Singapore, available at: https://www.cia.gov/library/publications/the-world-factbook/geos/sn.html, accessed on 20.05.06.

Bank had reclassified the former as newly industrialised economies and the latter as rapidly industrialising countries.

In the literature, the economic growth of both countries is explained through Malaysia's and Singapore's rapid industrialisation process. This was enabled by their comparative advantage in providing cheap and relatively skilled human resources for attracting FDI in high-tech manufacturing sectors. Thus, both countries depend more on multinationals than local firms to lead their industrialisation process. This differentiates Malaysia and Singapore from other latecomer economies such as Korea, Taiwan and Hong Kong where local enterprises have played a more dominant role (Jomo, 2003: 1-9; Hobday, 2000). Nonetheless, as the economies of the two countries became more sophisticated and wages rose, Malaysia and Singapore both realised that they were no longer competitive with the lower wage economies. This forced them to develop more sophisticated industries and increased their interest in the so called knowledge-based economy – which eventually pushed them to participate in the development of new emerging technologies such as biotechnology, nanotechnology and fuel cell technology. This is quite different from their previous industrial development or catching-up strategy, where the focus was more on developing technologies that are already well-established in the advanced countries.

4. Challenges to latecomers: Insights from the experience of Singapore and Malaysia

In the case of fuel cell technology, Singapore's superior economic performance is somehow reflected in the higher development of system functions of its fuel cell innovation system. Even though active participation by Singaporean actors in this technology started a bit later than Malaysia, it has managed to develop various system functions in the technology much more rapidly than the latter[18]. This is an intriguing situation. What are the key factors that have promoted the development fuel cell system functions in Singapore but have hindered similar development in Malaysia? How can such insights be useful for increasing our understanding of the challenges that latecomer countries have to face in their attempt to participate in the development of an emerging technology like fuel cells?

This section will try to answer these questions in step-wise way. It begins by describing more explicitly the ways in which the development of system functions in fuel cells is considered higher in Singapore compared to Malaysia by using the eight system functions already described in Section 3 (Sub-section 4.1). It will then proceed to the most important part of the article, where salient factors that be used to explain the higher development of system functions in Singapore is explained (Sub-section 4.2). The section end with a short discussion on how such insights can provide lessons to latecomer countries in their attempt to enter early into the development of fuel cell technology (Sub-section 4.3).

[18] Malaysia started the development of fuel cell technology in the early 1990s, while Singapore started in the late 1990s.

4.1. Higher development of system functions in fuel cells in Singapore compared to Malaysia

This section compares the development of the system functions of fuel cell technology between Malaysia and Singapore. Relative comparison of the state of system function development between the two countries is summarised in Table 3 followed by a brief description of how the assessment was made. It is evident from this assessment that the overall development of system functions in fuel cells is higher in Singapore than in Malaysia.

Table 3: The state of system function development in fuel cell technology: Relative comparison between Singapore and Malaysia

	HIGHER	LOWER
Singapore	Knowledge development Knowledge diffusion Direction of Search Legitimation Resource mobilisation (Financial and human resource) Entrepreneurial experimentation Market formation	
Malaysia		Knowledge development Knowledge diffusion Direction of Search Legitimation Resource mobilisation (Financial and human resource) Entrepreneurial experimentation Market formation

Note: The function 'positive externalities' is not included in this analysis due to the lack of data.

Knowledge development*:* The level of knowledge development in Singapore was higher than in Malaysia for all the relevant outputs – number and types of journal publications, commercialized patents and research projects. Knowledge development in Singapore had higher technological coverage through active involvement in three types of fuel cells (i.e. PEMFC, DMFC and SOFC) at various levels of system integration. In Malaysia, activities were predominantly focused on PEMFC.

Entrepreneurial experimentation*:* By the end of 2007, Singapore had more entries in fuel cell businesses than Malaysia, with higher participation by foreign firms and new start-ups. Also, entrepreneurial experimentation in Singapore had attracted higher involvement by leading firms in fuel technology with substantial support from the government. However, it should be noted that entrepreneurial activity in both countries is still in the early stages.

Direction of search: Direction of search in Singapore is more developed compared to Malaysia, not only in terms of the number of stakeholders involved in these activities, but also in terms of its positive evolution. In Singapore, activities were conducted via the national technology foresight initiative for energy industry and a public/private Fuel Cell Programme. Both platforms were tightly managed by government agencies and involved the participation of a wide range of local and international stakeholders. The recommendations from these initiatives were observed to be in line with current progress at the wider system level. In Malaysia the development of this function was based university-based fuel cell research programme and on the establishment of a roadmap for solar, fuel cells and hydrogen by a national level committee elected by government. But unlike Singapore, stakeholder participation in these activities in Malaysia has been more limited and there is little indication that the results of the roadmap have been influential at the system level.

Legitimation: The level of legitimation in fuel cell technology in Singapore was clearly much higher than in Malaysia. This was based on the continuous support for the technology from key players in the country, namely three influential government agencies and Rolls Royce, a foreign multinational company with a long standing business relationship with the Singaporean government. In Malaysia, legitimation for the technology was more evident at the beginning, particularly through interest expressed by a few key public and private actors in the energy industry. However, in later years, the interest of these key actors in the technology dwindled due to changed priorities.

Market formation: In both countries, the formation of local markets for fuel cells is very much in its infancy. However, efforts to harness export markets have shown more progress. In Singapore, this can be seen: (i) in the interest of the global company Rolls Royce to set-up its R&D and manufacturing facilities for the development and production of its SOFC products in Singapore; (ii) the flourishing test-bedding projects by powerful multinationals to tap into South-east Asian market for fuel cell related products; (iii) current exploitation of export markets by local start-ups. Similar efforts to form export markets in Malaysia can be seen from the activities of a local company, ETI Tech and multinational company, Agni Sdn Bhd. However, the formation of export markets in Singapore involved more participation by several actors in the system, while in Malaysia it was much more confined to individual business decisions. However, it is still very early to determine how far this targeting of export markets could progress in the future.

Resource Mobilisation:

- **Finance:** In Malaysia, system level financial mobilization for fuel cell technology was very dependent on public research funding from the government, and some public/private funding from the energy sector. In total, the amount of funds mobilized at system level was less than £6 million. In comparison, financial mobilization in Singapore was much higher and was available not only to support research activities, but also for other purposes. Initially, fuel cell activities in Singapore were dependent on research funding from two government agencies responsible for the funding of education and the development of science & technology - but over time, funding for various demonstration activities was made available by other types of government agencies, including those responsible for industrial development, environmental protection and the military. In addition, Rolls Royce, together with a consortium public/private local actors injected million dollars venture capital for R&D and manufacturing of SOFC products in the country. In total, system level financial mobilization in Singapore reached more than £50 million.

- **Human resource***:* Again, the development of this function was much more active in Singapore than in Malaysia. In Singapore, trained human resources in fuel cells are used to support the activities in universities and local PRIs, and to assist local and foreign firms. This was especially evident after the establishment of the national level public/private fuel cell programme - where human resources from the universities and local PRIs collaborated with Rolls Royce to meet the objectives of a national level industrial project. In Malaysia, there is no clear evidence that trained human resources in fuel cells were being mobilized in other parts of the system other than amongst the universities.

Knowledge diffusion: Similar to knowledge development, knowledge diffusion in Singapore is more active than in Malaysia – both locally and internationally. There was a bigger range of actors involved, the activities had a much more diverse platform and more specifically catered to different areas of fuel cells than in Malaysia. Another important distinction is in the higher level of awareness amongst actors in Singapore about the activities being conducted by different actors in the system.

4.2. Factors influencing higher development of system functions in Singapore compared to Malaysia

What is the explanation behind the higher development of system functions in Singapore compared to Malaysia? This section described a number key factors that the research have identified to be relevant in explaining this situation, which includes (i) Diversity of actors and the alignment of their activities; (ii) Synergy between energy, environment and industrial policies; (iii) Openness to internationalisation policies (iv) Responsiveness to demand-side policies. These are discussed accordingly in the following.

4.2.1. Diversity of actors and the alignment of their activities

One of the most obvious differences between the Singaporean and Malaysian fuel cell innovation system is the diversity of actors that are involved and the alignment of their activities. At least it can be said that the bigger contributions of three types of actors, in particular (government agencies, firms, local public research institutes (PRIs) have resulted in higher development of system functions in Singapore compared to Malaysia (see Table 5). It has also been observed that the development of fuel cell technology in Malaysia is more university-led, with less active participation by other actors.

There are clear differences in the roles of government in Malaysia and Singapore and the latter appears to be more hands-on than the former. The Singaporean government, particularly through the role of EDB and A*STAR, has provided extensive administrative, infrastructural and political support for various actors in almost all areas of system function – while in Malaysia, government's role has been confined mainly to supporting university activities. The differences in the contributions of these two governments has had a clear impact on the overall development of system functions in these countries. It should also be noted that the types of government agencies that are actively involved in the development of fuel cells in Singapore are more diverse than in Malaysia. This includes those agencies that are in-charge of industrial development (Economic Development Board or EDB), energy efficiency and environmental protection (Ministry of Environment and Water Resources or MEWR), development of science and technology (A*STAR), housing (Housing Development Board or HDB) and defence (Ministry of Defence). Furthermore, close cooperation between A*STAR and EDB has been very important in integrating the activities of different actors in almost all areas of system function. In the future, closer integration between different government agencies under the newly established Clean Energy Programme led by influential figures such as the ex-prime minister of Singapore, has the potential to further enhance this coordination. In Malaysia, only one government agency involved in energy policy i.e. the Ministry of Energy, Water and Communications (MEWC) played an active role in the development of the technology, and this provides fewer contact points for actors in the system to obtain administrative and political support from the government.

Another important difference between the Malaysian and Singaporean cases is the level of involvement by local PRIs in the development of system functions. In Singapore, four PRIs were actively conducting activities in fuel cells: Institite of of Materials Research and Engineering (IMRE) in the area of membrane development; Institute of High Performance Computing (IHPC) in computational modeling; Singapore Institute of Manufacturing Technology (SIMTech) in industrial manufacturing and Institute of Chemical and Engineering Sciences (ICES) in the area of catalyst. These institutes are not only conducting research in the technology, but are also producing publications, patents, conducting research supervision and providing industrial assistance. In Malaysia only two local PRIs have been involved in developing the technology, but their involvement has not been as active as that of their counterparts in Singapore. This is primarily because the involvement in fuel cell technology by both PRIs have been mostly oriented towards supporting university's research, and they have been less interested in conducting research activities for the wider innovation system. The management of R&D is also an important differentiating factor between Malaysia and Singapore. In Singapore, fuel cell R&D is under the management of a specific government agency, A*STAR. In the area of physical sciences, A*STAR has a specific role in supporting public sector R&D in fields essential to Singapore's manufacturing industry. The country's specific focus at the moment is on four industrial clusters: electronics, chemical, infocomms and engineering. Under this strategic direction, activities among the universities and PRIs can be easily coordinated to complement each other. In fact, it can be seen that the four clusters are actually in line with the research areas that are critical for fuel cells i.e. electronics (application for DMFC and PEMFC), chemical (development of membrane and catalyst), infocomms (complex modeling) and engineering (systems integration). Not surprisingly, these areas eventually have become the key elements of the country's national Fuel Cell Programme. In Malaysia, however the PRIs that are involved in fuel cell technology belong to two different agencies with different strategic directions: one under Ministry of Science, Technology and Innovation (MOSTI) and one under the Ministry of Energy, Water and Communications. Even though MOSTI does support R&D activities that are essential for other ministries, its orientation is much more general (i.e. developing energy or environmental technology) and it is less able to coordinate activities that are more specific to fuel cells.

Firms, particularly large energy-related firms, have made an important contribution to functional development in both countries, but their roles have developed in different ways. In Malaysia, Petronas and TNB, two of the country's biggest local government-linked corporations (GLCs) have been particularly important in creating initial exposure of the technology (particularly through their business networks) and this was used to encourage fuel cell research in the universities. However, TNB's and Petronas's interest has declined considerably and this seems to coincide with weak system function developments in Malaysia. Even the universities' contribution has been affected. Currently, both firms have mixed views about the role of the universities in the technology: on the one hand, they agree that government should support university fuel cell research as a creative academic activity, but on the other hand, they do not think fuel cell is the priority technology for development in Malaysia. In fact, Petronas and TNB, together with the government agency, MEWC are of the opinion that the development of other technologies, such as biofuel and nuclear, is more viable. The situation in Singapore is quite the opposite. The universities' early involvement was not induced by firms, and was mainly dependent on the activities of the university researchers themselves. In fact, interest from firms and government agencies in universities' activities was totally lacking to begin with. However, the situation started to changed dramatically when a British multinational firm, Rolls Royce, established its fuel cell manufacturing and R&D centre in Singapore. From then on, attention and support for university contributions to various aspects of system functions increased hugely. It is important to highlight that even governmen's significant role via EDB in the development of fuel cells is closely connected to their interest in supporting firms. EDB is Singapore's lead agency responsible for sustaining Singapore's position as a global hub for business and investment. In order to achieve this goal, they have a core mission to build linkages between firms, especially foreign multinationals, and relevant actors in the local innovation system to develop promising industries for the country. In the case of Rolls Royce, this is relatively easy due to EDB's close relationship with Rolls Royce for nearly 50 years, particularly in the marine and aerospace industries.

4.2.2 Synergy between energy, environment and industrial policies

In Malaysia, the development of system functions in fuel cells was deeply influenced by the renewable energy policy, while in Singapore, industrial development and environmental protection policies were much more influential. Furthermore, both countries have different endowments: Malaysia is a medium sized country rich in natural resources, while Singapore is a small city state that has extremely limited natural resource but has established itself as an efficient location for regional business headquarters. This has provided different policy priorities for different actors to manoeuvre their activities. It is argued here that the broad policy conditions in Singapore compared to Malaysia, are more compatible and timely for the various actors to enhance their contribution to the development of fuel cell technology.

In Singapore, the interest of key players in the industrial policy arena, such as EDB, A*STAR and private actors, to transform Singapore into a business hub for clean energy technologies, and the interest of the environmental policy community led by MEWR in increasing the country's image as a clean city (both in terms of increasing urban air quality and energy efficiency) have been progressing positively for some time. In the later period, both industrial and environmental policies in Singapore have been mutually enhancing. This is not only because of similar interests in supporting demonstration projects for clean energy technologies, but also because of heightened global commitment to the mitigation of climate change. Climate change issues have provided the necessary platforms for both policy communities to use the environmental and economic merits of fuels cells to align global environmental concerns with the country's interests in marketing Singapore as a clean city and a business hub for clean energy technologies. With the powerful presence of Rolls Royce, positive synergy in the policy environment has dramatically increased the interest of various actors to support the development of fuel cells in the country.

The interests of the Malaysian energy policy community in promoting the development of renewable energy has been progressing very slowly and it continues to lag behind the dominance of natural gas. Also, popular alternative energy options in Malaysia, such as biomass, nuclear and hydroelectric power, are the technology options that could be used directly without the need for a conversion technology such as fuel cells.[19] As a result, although the community's interest in fuel cell technology has been encouraging, actual policy commitment to support the specific development of the technology has been rather general at best, and has actually decreased overtime. This is evident in the declining interest of key players within the Malaysian renewable energy arena such as MEWC, TNB and Petronas. However, even with decreasing commitment from the renewable energy policy community, renewable energy policy has been the sole policy driver of the technology. It is clear, therefore, that the policy environment in Malaysia is relatively weaker than in Singapore and thus it can be concluded that the policy arenas that are being associated to fuel cells in this country provided space for different actors to manoeuvre and grow, compared to those in Singapore.

Indeed, the importance of the policy context for driving the development of fuel cell technology can also be observed internationally. As highlighted in OECD (2006) countries involved in the development of fuel cell technology are more inclined to benefit from a variety of policy drivers, depending on their local endowments, capabilities and priorities. This is clear if we examine the geographical and historical contexts of Malaysia and Singapore. In Malaysia, from the beginning, the interest in cleaner energy technologies, such as fuel cells, was closely embedded within the country's interest in increasing the use of renewable energy, particularly in relation to the country's rich natural resources in hydropower, solar energy and biomass. In Singapore, interest in clean energy technology was associated with its acute need as a small country with among the highest energy consumption in the world, to increase its performance in energy efficiency. Also to maintain its image as a clean city and business hub, Singapore has a strong interest to use the development of clean energy technologies, like fuel cells, as a future economic driver.

4.2.3 Openness to internationalisation policies

Another key policy difference between the Malaysian and Singaporean universities is their level of internationalisation. In comparison to Malaysia, Singapore has had an extremely open policy for encouraging active and tight foreign participation in the development of its economy, in both

[19] This is because bio-fuel, hydropower and nuclear power can be used either directly to generate electricity or as a fuel to generate hydrogen to be used in fuel cells.

the private and public sector. This high level of internationalisation translates into policies and practices in the universities and PRIs. For instance, one of the main funding sources for universities' research activities in Singapore is managed by a special committee chaired by renowned researchers from international universities and research institutes including MIT from the USA, Oxford University from the UK, the Max Planck Institute from Germany and the National Natural Science Foundation from China. Also, nearly half of the researchers in Singapore's universities and PRIs are foreigners, who receive high salaries for holding important research positions in these organisations, and have sufficient freedom to make active contributions to the development of the fuel cell innovation system in Singapore. For instance, there is a researcher from China, Mr Han Ming, who is a PhD student in a local university and a part time researcher both in a PRI and a local firm, and also one of the founders of the Singapore Fuel Cell Community based in local polytechnic. Similar observation were also observed in the case of a number of other researchers as well. In Malaysia, even though internationalisation is considered important for the universities, its implementation has been more cautious due to perhaps, Malaysia's overarching social priority in ensuring the welfare of Bumiputra staff and students in higher education (Lim, 1995). As a result, foreign researchers receive fewer incentives and have fewer opportunities to extend themselves within Malaysian fuel cell innovation system, which might explain why their contributions are smaller than those of their Singaporean counterparts.

In addition to the international composition of their staff, students and advisors, Singaporean universities are expected and explicitly instructed by the Singaporean government to undertake various types of collaborative activities with international actors. This strong pressure to internationalise research is not apparent in Malaysian universities. This is especially evident in relation to the universities' fuel cell research programme. Since the beginning, Malaysian universities' activities have been oriented towards developing the country's indigenous technologies, exploiting local markets and attracting the participation of local firms. The activities of Singaporean universities are not based on a nationalistic orientation. In fact, in all areas of system function, the activities of Singaporean universities have a much more outward priority, i.e. to develop the technology for Rolls Royce, to exploit export markets and to attract the participation of foreign firms. The universities' nationalistic orientation (i.e. in developing made-in Singapore fuel cell product) has only been encouraged by government after the country's main objective of exploiting international opportunities was achieved.

4.2.4 Responsiveness to demand-side policies

One of the key strategies of the industrial and environmental policy communities in Singapore has been to support the development of demonstration or test bedding projects for clean energy technology. Demonstration projects play an interesting part in the development of fuel cell technology – not only are they essential for understanding how the technology can be developed, but they also show how it can be effectively diffused and used in a particular locality. Therefore, they bring multiple benefits to system function development, both in the obvious area of knowledge development and diffusion, and also by increasing legitimation, attracting entrepreneurial experimentation and seeding market formation. Thus, demonstration projects are essential for enhancing both the supply and demand sides of the innovation process.

Based on these benefits, the relevant government agencies in Singapore, such as EDB, MEWR and HDB have played an active role in bringing foreign firms such as Daimler Chrysler, Segway and Idatech, to conduct demonstration projects in Singapore (for different types of transport application and a stationary application), and have included local universities, local firms and polytechnics in these initiatives. They have also extended demonstration projects to a higher level of system integration by attracting British Petroleum (BP) to test fuel cell applications with a hydrogen refuelling system. It is important to note however that demonstration projects in Singapore is also related to the country's higher level policy to market itself as a global clean energy business hub in Asia. The Singaporean government uses energy, environmental and technological rationale to attract foreign players to invest and establish their operations in the city state. By early 2007, Singapore has institutionalised this process through the establishment of the multi-agency Clean Energy Programme Office or CEPO – with its objective in making Singapore a global test-bed for early adoption of clean energy products and solutions.

In Malaysia, no clear demand side policies for fuel cells were detected. Demonstration projects are scarce, and mostly implemented by the universities with little support from other actors. Furthermore, unlike Singapore, the development of fuel cells in Malaysia has been much more related to R&D policy with no clear connection to industrial policy. Even the involvement of government agencies has been focused more on encouraging R&D rather than on the diffusion or adoption of the technology. As a result, the development of fuel cells in Malaysia has been rather unbalanced – with lot of activities on the supply side, but with no sufficient demand to progress the innovation process forward.

5. Discussion: Lessons for latecomer countries

Fuel cell technology, as an emerging technology, has specific characteristics that need to be carefully considered by latecomers in their attempt to be involved in its development. In view of its specific characteristics, fuel cell technology is currently at the later stage of the emerging phase, a phase that interestingly, has persisted for more than 100 years. In a context of fluctuating periods of success and failure throughout its history, whether the technology will ever progress from this stage is still an open question. Fuel cell technology is also a highly dynamic technology, with shifting dominance in different types of fuel cells and application within different periods. Also during its long introduction phase, various activities by different types of actors have taken place, with high involvement by governments and private sector, including those involved in well-entrenched industries. In this sense much of the technology has been appropriated by large companies or public-private entities in the advanced world. This might have a significant implication for latecomers, as the availability of accessing and exploting technological knowledge is quiet limited[20]. In addition, when fuel cells is viewed within the perspective of a functional and workable technical system, participation in this technology requires a mastery on various areas of expertise, from the most novel (fuel cell stacks and the use of pure hydrogen from sustainable sources) the more established parts (BOS, fuel cell applications and the use of hydrogen from fossil fuel) of the technology. Therefore in this case, capability in system integration is an essential requirement for handling the development of the

[20] Perhaps such windows of opportunity are more prevalent in the field of biotechnology where public R&D has a much bigger and stronger role in generating inventions for commercial exploitation and in laying the foundation for firms' innovative efforts (OECD, 2006: 26).

technology in an effective way. This is the reason why public-private partnerships, particularly theough demonstration activities, are being conducted extensively at various levels, be it locally, regionally and internationally, to address this challenge. Finally, because of its complexity and relevance in addressing the global issue of climate change, fuel cell technology is highly influenced by three policy areas i.e. environmental policy, energy policy and industrial policy.

Connecting these characteristics to the situation in Singapore, one could instantly deduce why the development of fuel cell technology in this country was able to fluorish much more effectively than in Malaysia. As discussed in Section 4: Sub-ssection 4.2, the four factors that are stronger in Singapore are clearly conducive to address these key characteristics of the emerging phase of fuel cell technology:

- Higher diversity of actors and the alignment of their activities provides more integrated capabilities to address the dynamic nature of the technology, and to handle various areas of its technical system, from the most novel to the most established.
- Higher synergy between energy, environment and industrial policies in Singapore allows the country to simultanously handle key policy areas that are currently shaping the progress of this technology. Such policy integration also provides the country with higher awareness and flexibility to exploit or overcome any on-going opportunities and challenges in the policy environment (particularly at the international level).
- Higher openness to internationalisation policies gave more opening for Singapore to establish strong and stable relationship with international partners – particularly influential private actors in the advanced countries that has more experience in the development of this technology like Rolls Royce.
- Higher responsiveness to demand-side policies, particularly in the area of demonstration, provides strategic space for actors in Singapore to be involved in activities that are also of interest to advanced players in the technology e.g. Daimler Chrysler, Segway and BP.

In this regard, the main lesson that one can gain from this observation is that latecomer countries need to understand the game that they play when participating in the development of emerging technologies - which can be very specific to a particular technology area that they are involved in. The main characteristics of fuel cells as an emerging technology, for instance, is its long history of emergence, high level of system integration and its embeddedness within a range of established sectors. The development of this technology is also very political, as it is related to two very globalised and politically charged policy arenas: energy policy and environmental protection. As shown in the case of Singapore and Malaysia, the game of participating in this technology needs strong capabilities in coordination, integration, internationalisation and demonstration. Without such capabilities, the chances to be involved in this technology can be very limited.

6. Conclusion

This article has demonstrated that the systems of innovation approach (in this case using the technological system framework and analysis of system functions) can provide insights for understanding the challenges that latecomer countries have to face in the development of an emerging technology like fuel cells. It shows that the higher development of system functions in fuel cells in Singapore is shaped by four possible factors: diversity of actors and the alignment of their activities; synergy between energy, environment and industrial policies; openness to internationalisation policies; and responsiveness to demand-side policies. In Singapore the stronger presence of such factors in its policy environment has had a positive influence on the development of system functions. In contrast, the absence or weaknesses of these features might have contributed to the weaker and more unbalanced development of system functions in Malaysia. It is argued that this is mainly because these factors were effective in addressing specific characteristics of the emerging phase of fuel cell technology.

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