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Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development

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ABSTRACT

This paper investigates Danish and American hydrogen fuel research from a modified technological innovation system (TIS) perspective. We ask: which approach to hydrogen research is more effective, and what do the differences between the two cases tell us about the research process and theories of innovation? To answer these questions, we begin by justifying our selection of hydrogen systems and Denmark and the United States as our case studies. We proceed to introduce a modified theoretical framework of TIS and focus on seven core elements of hydrogen research: knowledge development and diffusion, entrepreneurial experimentation, political and social influence, market formation, legitimation, resource mobilization, and positive externalities. We conclude by offering insights from our comparison as they relate to hydrogen research strategy and policy, effectiveness at achieving national goals, and the need for further research and better conceptual models about innovation.

1. Introduction

Globally energy systems are undergoing a critical transition in order to reduce CO_2 emissions (Van den Bergh et al., 2011). This transition is driven in part by growing concern over climate change, the scarcity of fossil resources, and the geographically uneven distribution of traditional energy resources (Brown and Sovacool, 2011). This transition will undoubtedly be technological costly and socially difficult, predicated on the co-evolution of institutions, systems, technology, and entrepreneurial activities (Jacobsson and Bergek, 2004; Nygaard, 2008). It is therefore important to apply a systemic view of the transitional changes that have to take place, and to examine the way in which actors, institutions, historical momentum, and the broader social and political environment interact to promote, or constrain, innovation (Araújo, 2014; Fri and Savitz, 2014). In this regard, Sovacool (2014) notes that “work on national systems of innovation … [has] much to contribute to the field of energy studies.”

This article focuses on one such technology, hydrogen fuel cells, and two sets of sociopolitical environments where innovation is occurring, those in Denmark and the United States. In Denmark the government has agreed upon an ambitious energy policy for the period 2012–2020 stating that 50% of electricity consumption must be covered by wind power by 2020 (Danish Ministry of Climate Energy and Building, 2012), and furthermore that the national system, including transport, must be completely CO_2 free by 2050. The United States, while it has not yet introduced such sweeping climate policies, is still the world's second largest energy consumer and emitter of greenhouse gases, and it has implemented two massive changes in policy over the past decade, the Energy Policy Act of 2005 and the Energy Security and Independence Act of 2007. These two pieces of legislation have been intended to enhance the competitiveness of the U.S. energy sector and to promote innovative technologies. For these reasons, both countries have invested heavily in hydrogen research and technology, and both are considered global market leaders.

In this paper, we investigate Danish and American hydrogen fuel research from a modified technological innovation system (TIS) perspective. We ask: which style or approach to innovation is more effective for hydrogen fuel cell research? To provide an answer, we build on the knowledge about the topic of energy system transition processes, and more specifically innovation system build up around hydrogen fuel cell technologies, which has been described by e.g. Van den Bosch et al. (2005), Taanman et al. (2008), and Sartorius (2008), but not yet applied to a comparative study of Denmark and the United States. Drawing from the basic theory of incremental versus radical innovation by Tushman and Anderson (1986),

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Abbreviations

DMFC	direct methanol fuel cell
DOD	Department of Defense
DOE	Department of Energy
FCH-JU	fuel cell and hydrogen joint undertaking
HT-PEM	high temperature proton exchange membrane fuel cell
LT-PEM	low temperature proton exchange membrane fuel cell
NIS	national innovation system
NREL	National Renewable Energy Laboratory
OECD	Organization of Economic Cooperation and Development
RIS	regional innovation system
SGIP	(Californian) Self Generation Incentive Program
SMEs	small and medium sized enterprises
SOFC	solid oxide fuel cell
TIS	technological innovation system

and the research of hydrogen vehicle development of Van den Hoed (2007), it is clear that the incumbents within the industry will defend their core business, and only introduce radical new technology when forced to by external factors. Recent research about the global development of the hydrogen vehicle innovation system shows that it is indeed fast developing and that it may soon move into the growth phase of technology diffusion, provided that requisite policy support continues (Köhler et al., 2013).

We begin our study by explaining why we selected hydrogen technologies for analysis and Denmark and the United States as our two cases. We introduce the theoretical framework of technological systems of innovation and describe how it applies to the cases investigated here. The next part of the paper focuses on seven core elements of hydrogen fuel cell research for each case: knowledge development and diffusion, entrepreneurial experimentation, political and social influence, market formation, legitimation, resource mobilization, and positive externalities. The study concludes by offering insights from our comparison for analysts of research and innovation as well as policy recommendations for those concerned with hydrogen development.

In proceeding on this path, we make at least two contributions, one theoretical, and one practical. Theoretically, previous research has shown that the overall structure and efficiency of hydrogen research follows diverging trajectories in different national and institutional cultures. In their earlier work, Spencer et al. (2005) argued that national political institutional structures for innovation can differ organizationally and socially. They suggest that such institutions can fall into four quadrants: social corporatist; state corporatist; liberal pluralist; and state nation. They note that Denmark is a typical example of a social corporatist country and that the United States is a typical example of liberal pluralist nation. In social corporatist nations (Denmark), the role of the state is to facilitate and not to dictate, whereas in the liberal pluralist nations (the United States), the state is relatively weak and has thus a smaller role in technical development. Similarly, Garud and Karnøe (2003) investigated industrial development in the Danish and the American wind industry and suggested that in one case, Denmark, innovation occurred from the bottom-up at relatively low cost, whereas in the United States, it was more costly and occurred from the top-down. Whitley (2000) also explored the institutional structure for innovation in capitalist countries and found that the United States was more corporatist, fragmented, and even destructive. The result of this is that firms that could not compete went bankrupt. The Danish environment, by contrast, was more cooperative, publicly supported, and coordinated (Whitley, 2000). Sovacool (2010) compared Danish and American research "styles" on energy systems and concluded that the Americans were highly centralized and focused on radical change whereas the Danes were decentralized and focused more on learning-by-doing and incremental refinements (Sovacool, 2010). Our study enables us to test the validity of these theoretical suppositions by asking: How does a hydrogen TIS rooted in competitive liberal pluralism aiming for radical change differ from one rooted in collaborative social corporatism aiming for incremental improvement?

Practically, our study reveals a set of lingering challenges—economic, social, technical, and political barriers—that impede the ability for both Denmark and the United States to capitalize on previous hydrogen innovations and reach commercialization. In other words, we show how neither country is particularly impactful in its approach to hydrogen fuel cell research, and in doing so, we point the way for policy reforms that might be crafted to address these barriers. Here, our study has practical and policy value by asking: How can the hydrogen research process be improved?

2. Case selection and research methods

We began by selecting hydrogen fuel cells for analysis. This is because such technologies are unique in their modularity and end-use variety: they can serve a variety of niche markets and sectors ranging from electricity supply to transportation, in some cases cost-competitively (Brown et al., 2007a). They can also, as Vasudeva (2009) indicates, follow a number of distinct technical pathways shown in Table 1, each with their own strengths and weaknesses. Current commercially available hydrogen fuel cell applications include backup power solutions and off grid power supply with products ranging from few watts for small electronics to several hundred kW (see e.g. Brown et al., 2007b; Fuel Cell Today, 2013a). Furthermore, hydrogen fuel cells can play important future roles in large-scale energy storage, energy balancing for regulatory power, the provision of domestic heat and power, and mobility (e.g. in hydrogen cars), and more (Dunn, 2002; Larminie and Dicks, 2003). The biggest and most valuable markets for these technologies in the future are probably automotive and residential heat and power (Fuel Cell Today, 2013b; Voelcher, 2013).

That said, hydrogen fuel cells have historically also been subject to unrealistic expectations (Bakker and Budde, 2012; Sovacool and Brossmann, 2010). This has had a twofold influence on its development: On the positive side, decision-makers in government and industry have committed themselves to accelerated research efforts (Suurs et al., 2009). On the negative side, the technology has proven more complex than initially expected and projected targets in various national roadmaps have been missed (Suurs et al., 2009; Verbong et al., 2008).

Hydrogen systems thus lack what sociologists call "closure" (Andreasen and Sovacool, 2014; Hård, 1994): they remain "open" to interpretation and their future development, and role in our future energy system, is contingent. Given the multiple technical pathways involved with their differing applications, hydrogen fuel cell technology is to a degree polysemiotic, offering multiple meanings for stakeholders who can view the technology with distinct interpretive frames, giving the technology "interpretive flexibility" (Sovacool, 2011). This makes hydrogen somewhat special in discussions of current state of the art energy systems.

To investigate the TIS surrounding hydrogen fuel cells, we apply a methodology described by Bergek et al. (2008b). We selected Denmark and the United States due to their economic commitment

Table 1
Positive and negative technical attributes of commercially available fuel cells.

Fuel cell technology	Attractive attributes	Undesirable attributes
Phosphoric acid (PAFC)	- Low temperatures suitable for portable device applications - Ability for variable power output - Broad fuel choice	- Uses expensive platinum as a catalyst - Electrolyte is poor conductor at low temperatures
Proton exchange membrane (PEM)	- Low operating temperature suitable for transportation and portable devices - High power density	- Uses expensive platinum as a catalyst - Sensitivity to fuel impurities
Molten carbonate (MCFC)	- High operating temperature improves efficiency for base load power plants	- Not suitable for small-sized applications
Solid oxide (SOFC)	- High operating temperature improves efficiency for base load power plants - Solid electrolyte improves conductivity	- Electrolyte is made from ceramics and solid zirconium oxide that is a rare mineral
Alkaline fuel cells (AFC)	- Low temperature and high fuel-to-electricity efficiency	- Requirement of pure hydrogen and allergic to carbon dioxide
Direct methanol fuel cells (DMFCs)	- Eliminates need for fuel reformer drawing hydrogen directly from the anode - Low temperatures suitable for portable devices	- Fuel crossing from anode to cathode without producing electricity
Regenerative fuel cells	- Closed loop, regenerating water from which hydrogen is drawn	- Additional energy requirements to split the water molecule
Zinc-air fuel cells (ZAFC)	- Regenerative, closed loop - Abundance of zinc reduces material costs	- Additional energy to regenerate zinc oxide
Protonic ceramic fuel cell (PCFC)	- Exhibit benefits of both high and low temperature fuel cells	- Electrolyte is made from ceramics and solid zirconium oxide that is a rare mineral

Source: Modified from Vasudeva (2009).

to hydrogen. Fig. 1 presents an overview of the funds given to research and development within hydrogen and fuel cell technology by different countries in the Organization for Economic Cooperation and Development (OECD) over the past decade. Fig. 1 illustrates that the United States spent the most as a total (out of all OECD countries) at slightly more than €2 billion in 2012 prices and exchange rates; Denmark spent the most per capita in the same period at roughly €38 per person. Furthermore, hydrogen and fuel cell technology is among the renewable energy technologies to receive the most RD&D funding these years, which makes the technology an interesting topic for analysis.

For each case study, empirical knowledge has been derived through a literature review conducted during the period November 2013–March 2014, supplemented with original research undertaken by one of the authors in their dissertation (Andreasen, 2014). Our primary tool, a literature review, was aimed predominately at peer-reviewed energy studies journals, but we have included publicly available reports and governmental publications when relevant. Further details about the empirical data collected for the study, our secondary tool, are summarized in Andreasen (2014).

3. Unveiling a modified technological innovation systems theory (TIS)

TIS theory is applicable when investigating the divergent innovation processes for how specific technologies evolve. The national boundaries set up in the specific analysis in this paper are to some extent artificial, considering that stakeholders operate across borders for both tangible and intangible resource acquisition and for market formation activities. However, TIS has the advantage of properly limiting the scope of the research topic to bring a given technology or research program into sharp focus, enabling the comparison of national development trajectories, and giving the researcher the opportunity to investigate the interaction in the network of agents and institutional settings. It also offers a useful framework for revealing sites of friction and institutional resistance which impede the commercialization of a new technology (Hellsmark and Jacobsson, 2009). In this regard, TIS is closely aligned with the “Technologies, Markets, and Organizations” Innovation Framework presented by Hajek et al. (2011) and Ventresca and Hajek (2010).

To those unfamiliar with the topic of innovation and theories of change, “innovation studies” have been widely investigated since the 1930s where Schumpeter studied innovation within organizations (Schumpeter, 1934). This led to innovation system studies, an interdisciplinary field of enquiry drawing from business development, engineering, marketing, organizational design, and research policy (Freeman, 1987; Lundvall, 1985). These efforts culminated in the introduction of three related theories: national innovation systems, regional innovation systems, and technological innovation systems (see Edquist, 1997; Dosi et al., 1988; Balzat and Hanusch, 2004).

Table 2 gives a brief descriptive and comparative overview of these three theories. As Fig. 2 indicates, despite substantial variance between them, some commonalities exist. All three theories focus on the vertical integration within society (the system) and the innovation as an interactive process between actors (Lundvall, 2007), rather than focusing merely on the firm, actors, resources, or broader environments in isolation. As Hajek et al. (2011) write, innovation is complex and multi-causal, occurring at the nexus or “interplay between organization capabilities, evolving market structure and technological development, within the context of broader developments in the political, scientific, environmental, legal, economic and social spheres.” Musiolik and Markard (2011) add that the “emergence and development of a new technological field is a complex, multi-faceted process shaped by the strategic moves of innovating actors and by institutional structures, which support, guide, and also constrain technology development.” (Musiolik and Markard, 2011)

Nonetheless, for our study we selected TIS because it gives valuable insight to the dynamics of emerging technologies and operates nicely at the “meso” scale between national and regional

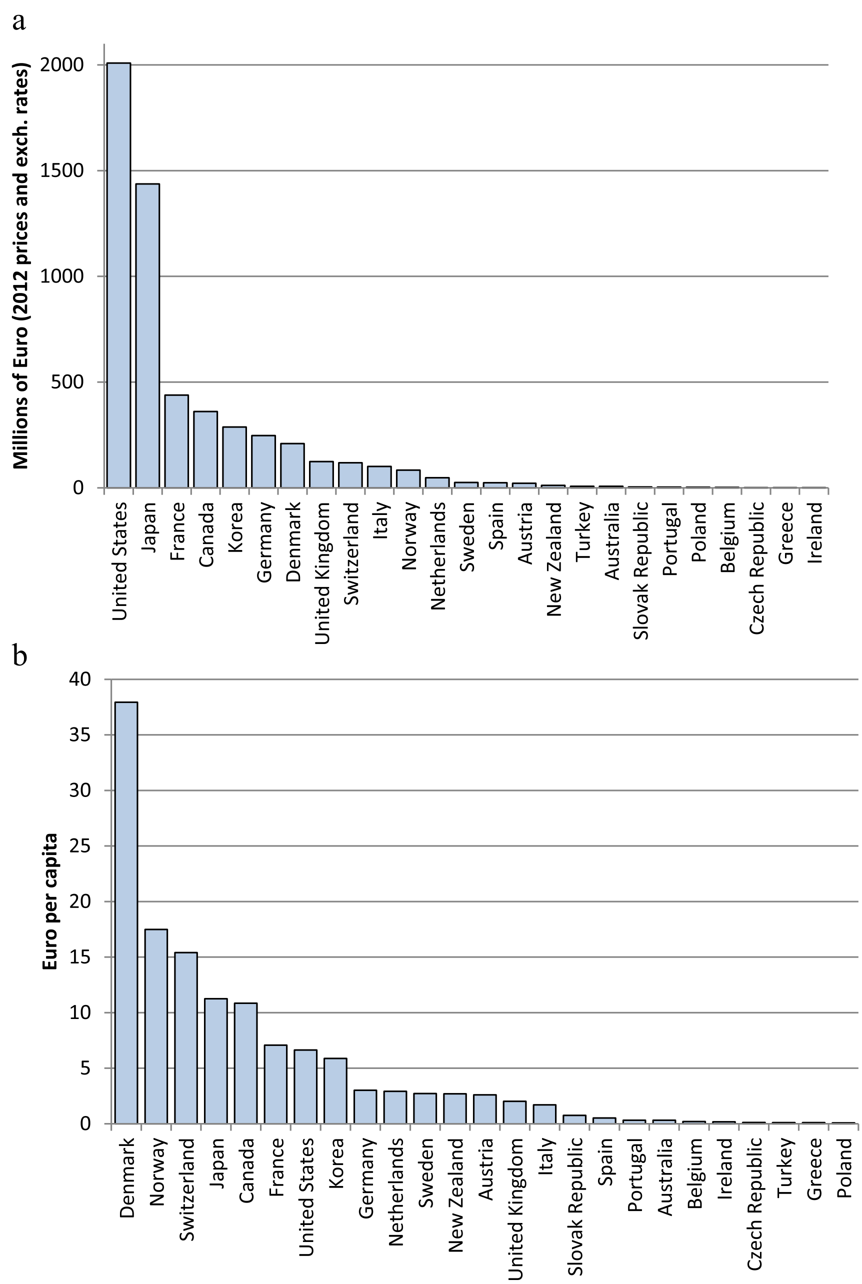

Fig. 1. Energy research expenditures on hydrogen energy, 2003–2012. (a) Total expenditures, (b) Expenditures per capita.

systems (Bergek et al., 2008a,b). Carlsson and Stankiewicz (1991) define a TIS as being "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology." Generally, this means a TIS is comprised of three mutually reinforcing components: actors, networks and institutions. The function of the innovation system is to diffuse and utilize new products and services in the market. One of the key characteristics of the TIS analysis is that structure is separate from function. Function can be defined either as a process or an activity that contributes to a development or diffusion of new products or services.

For the purposes of our study, we rely on the seven distinct functions summarized by Table 3. Hendry et al. (2008) add that institutional change is a requirement for technological change during the phase of entry to market. This will create "nursing markets" which makes it possible to evolve the new technology to a level where it is mature enough to compete with current technology systems. At this point the technology should be able to "live on its own" in the market without further institutional support (Bergek et al., 2008a).

As readers digest Table 3, we must note that we employ a slightly modified version of the "positive externalities" function in our study. Traditionally these are defined as "how investments by one firm may benefit other firms 'free of charge'" or as aspects that "magnify the strength of the other functions" (Hellsmark and Jacobsson, 2009). Within the realm of TIS theory, this has generally focused on things like improved labor for firms or intellectual

Table 2
Overview of national, technological, and regional innovation systems.

	National innovation system	Technological innovation system	Regional innovation system
Emphasis	Nation and state	Technological hardware or network	Innovation cluster encompassing nations and technical systems
Main actors	Industry, government, education and research organizations	Firms, nongovernmental organizations and individuals	Universities, industrial enterprises and public research organizations
Primary methods of influence	National policies, laws and financial support	Standards and regulations	Informal institutions depending of trust and reliability among the actors
Processes of interaction	Joint industry activities, R&D collaboration, technology diffusion and personnel mobility	Inter-industry cooperation and interactions among firms and non-firm organizations	Inter-firms interactions, external interactions for firms with research, organizations and R&D collaboration
Primary theory developers	(Freeman, 1987; Lundvall, 1985)	(Bergek et al., 2008a; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007)	(Chung, 2002; Madsen and Andersen, 2010)

Source: Adapted from Gao and van Lente (2008).

property patent pools. Because our study deals with energy, we take a broader view of "positive externalities" and list those that occur for society as a whole, such as reduced greenhouse gas emissions or improved energy security alongside the more traditional ones such as productivity or patents; this follows the definition of positive externalities offered by Musiolik et al. (2012).

4. Results and discussion

This section of the paper presents our two case studies. For each case it begins with a short introductory overview before organizing the remaining discussion around the seven TIS functions of knowledge development and diffusion, entrepreneurial experimentation, political and social influence, market formation, legitimation, resource mobilization, and positive externalities.

4.1. Fuel cell development in Denmark

In Denmark, fuel cell stakeholders have benefitted from an ambitious government policy regarding low-carbon energy system development (Danish Ministry of Climate Energy and Building, 2012). The realization of these targets requires buildup of supportive technologies well beyond the two that Denmark is most famous for: wind turbines and combined heat and power (Sovacool, 2013). Hydrogen and fuel cells are thus prioritized in Denmark as a possible key technology which can facilitate the much needed balancing of energy systems (Andreasen and Sovacool, 2014).

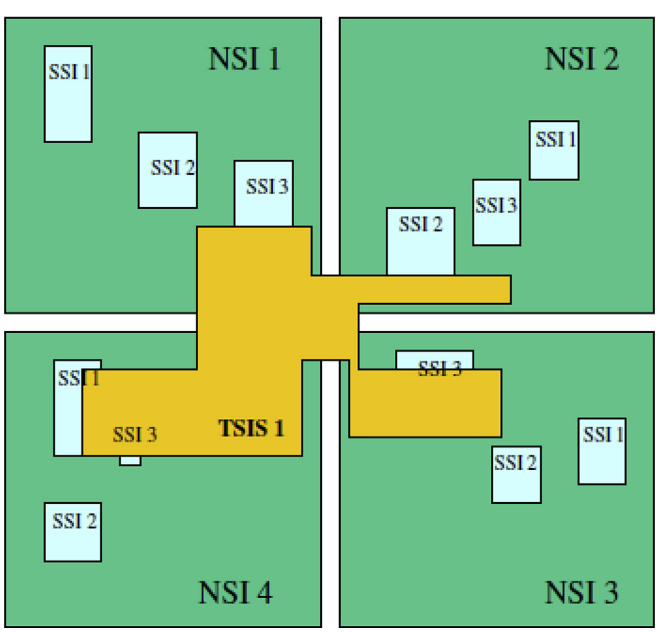

Fig. 2. Conceptualizing national, technological, and regional systems of innovation. Source: Hekkert et al. (2007). Note: NSI refers to National System of Innovation. TSIS refers to Technology Specific Innovation System. SSI refers to Sectoral System of Innovation (in this paper we use the term: Regional System of Innovation).

The Danish hydrogen and fuel cell landscape is split into actors involved in hydrogen technology development, such as electrolysis, hydrogen infrastructure establishment and hydrogen storage; and those involved in fuel cell technology development activities which primarily consist of research, development, and testing. In this analysis we have though chosen to consider these two as one group of actors, due to close collaboration between them and technological coherence between hydrogen and fuel cell technology.

The combined hydrogen fuel cell landscape consists of roughly 20 companies shown in Appendix A as well as a few supporting institutions and networks. These are primarily small and medium sized enterprises (SMEs) engaged in research and development activities in public/private partnerships with Danish Universities, although as Appendix C indicates, only 3 Danish companies are in the top 200 among fuel cell companies globally.[2] Collaborations are facilitated through the Danish Partnership for Hydrogen and Fuel Cells (*Partnerskabet for brint og brændselsceller* in Danish). The partnership is a formal institution with the aim to facilitate triple helix collaboration and thereby to promote the development and commercialization of hydrogen fuel cell technology. Besides the Partnership, there are a few minor networks with more specific narrow objectives. One of these is Cemtec, an industry sponsored network for companies localized in a specific geographical area of Denmark, and for hydrogen mobility there is the HydrogenLink network, which collaborates with other countries in Scandinavia and car manufacturers globally to expand infrastructure for hydrogen vehicles.

4.1.1. Knowledge development and diffusion

Within the Danish market, knowledge development occurs primarily in public–private partnerships as state funded research development and demonstration projects. These projects usually involve activities where at least one company and typically one or more universities and other institutions take part. Public funding is either supported by Danish national institutes or by European

[2] Please note that Appendix C only mentions one type of actor, "fuel cells," and therefore may not represent overall Danish market prevalence for hydrogen overall.

Table 3
Summary of the seven key functions to the TIS framework.

Function	Examples of measures
Knowledge development and diffusion	R&D projects Patents Bibliometrics Investments in R&D Learning curves Workshops and conferences
Entrepreneurial experimentation	Number of new entrants Diversification activities of incumbent actors Experiments with new technology Degree of variety in experiments (can both indicate early lifecycle through lack of standardization, or indicate widespread applicability for the technology)
Broader political and social influence	Taxes and prices Regulatory pressures (e.g. quota systems) Government/industry targets Stated future growth potentials Articulation of interest by leading customers
Market formation	Size and type of markets created Timing of market formation Drivers of market formation
Legitimation	Attitudes towards the technology among different stakeholders Influence from interest groups Lobbying activities Political debate in parliament, media and other influencing institutions
Resources mobilization	Volume of capital and venture capital Volume, quality and mobility of human resources (educational data) Volume, quality and accessibility of complementary assets
Development of positive externalities	Political power of TIS actors Activities to increase confidence Development of needed human capital/ knowledge Information and knowledge flows Collective social, environmental, and political benefits

Source: Adapted from Bergek et al. (2008a,b).

funding institutions like Fuel Cell and Hydrogen Joint Undertaking (FCH-JU). A typical measure for knowledge development is the amount of patents applied for and granted. In this regard, there is some evidence to suggest that Danish hydrogen research is weakening. According to the 2012 Fuel Cell Today Patent Review, Danish actors made 57 patent applications in 2011 and were granted 21 new patents (Fuel Cell Today, 2012). The Clean Energy Patent Growth Index reports that Denmark was granted only three fuel cell patents in 2013.

4.1.2. Entrepreneurial experimentation

The Danish TIS is distinguished by a market environment that stimulates collaboration and utilizes a targeted approach that sets goals or specific milestones and then provides public investment to firms with strong track records in achieving national priorities (Suurs, 2009). The main focus areas for Danish actors within this collaborative system are backup power supply solutions, off-grid power supply (this could e.g. be for mobile homes), and material handling vehicles. Experimental activities in Denmark are centered on a few key devices, namely LT-PEM, HT-PEM, DMFC and SOFC fuel cells and alkaline electrolysis, PEM electrolysis, hydrogen storage in metal hydrides and hydrogen fueling station for automobile development. The companies involved in development have created core competencies due to vested time and capital within their specific technological domain and are therefore reluctant to experiment with other technologies. There were new entrants to the fuel cell innovation system in the 1990s and during the hype period of the 2000–2008, however this has recently ebbed. Moreover, the average size of fuel cell units developed in Denmark ranges from only a few watts (DMFC) to kW (PEM, HT-PEM, SOFC). This relatively small range gives a low degree of variety in experimentation.

4.1.3. Broader influence

Two separate sets of hydrogen applications have attained the broadest social influence. The first is electricity. In 2012 the Danish government made a very ambitious energy agreement, in which the main topics relate to the transition from fossil based electricity production to renewable energy based on wind power (Danish Ministry of Climate Energy and Building, 2012). This incentivized entrepreneurs to develop and engage in market development tasks for hydrogen and fuel cell technology in the electricity sector as a way to store electricity and balance loads. With regards to residential heat and power solutions, there is considerable potential, at least in theory. The growth potential for residential heat and power solutions is approximately 25% of Danish buildings, the percentage not connected to district heating systems.

With regards to mobility there has been allocated a relatively meager $1.8 million for hydrogen infrastructure (Danish Ministry of Climate Energy and Building, 2013). Nonetheless, Denmark is, due to taxation, the country in Europe where it is most expensive to buy and own a car (Kunert and Kuhfeld, 2007). Battery electric cars and hydrogen cars are currently exempt from registration tax and vehicle excise duty, thereby making them more economically competitive to drivers. There are, however, no tax or price incentives in place to use hydrogen fuel cell technologies for other purposes. Future near-term growth potential for Denmark is primarily limited to the development and deployment of servicing and hydrogen fueling stations. However, over the long-term this may change. According to internal analyses (discussed during our research interviews) conducted by H2Logic, a leading manufacturer of hydrogen fueling stations, and HydrogenLink, a network for the development of a Scandinavian hydrogen highway, approximately half of the Danish automobile market could be comprised of hydrogen fuel cell cars in 2050, corresponding to approximately 1.4 million vehicles (The Danish Partnership for Hydrogen and Fuel Cell Technology and Hydrogen Link, 2011).

4.1.4. Market formation

Pure commercial markets in Denmark are still scarce, and the activities within hydrogen and fuel cell technology are primarily focused on creating markets. The early markets that have been explored in Denmark are backup power supply solutions where stand-alone hydrogen fuel cell units are in a standby state until needed. The advantage of this market is that the customers who buy backup power solutions often value energy security and reliability, which justifies the higher up-front costs of investing in hydrogen. Regarding the function of market formation, Danish companies are approximately at the same state as the rest of Europe, which means that they remain underdeveloped when compared to Japan and the U.S. (Fuel Cell Today, 2013a).

4.1.5. Legitimation

Considering the state takes part in most projects concerning hydrogen and fuel cell technology, either as active partner or as funds provider, there is high degree of legitimacy given to the hydrogen sector. Broad consensus exists that the Danish energy system must undergo a major transition (Lipp, 2007). Conventional battery electric cars have experienced mistrust from society due to recent bankruptcy of electric car pioneer BetterPlace. This engendered a marginally positive effect on hydrogen vehicles, since they can travel further on a single tank of fuel. According to our interviews, a consensus seems to exist stating that pure hydrogen should in the future primarily be used for light mobility purposes. For more energy demanding tasks, like heavy transport or energy storage, hydrogen is believed to be most useful as a way to refine lower grade biogas to natural gas quality, which can then be used to make liquid fuels or be connected directly to the natural gas system (Wittrup, 2013).

4.1.6. Resource mobilization

At least two large universities in Denmark teach special fuel cell programs (Fuel Cells 2000, 2014). Due to the geographic small size of the country, these universities are sufficient to provide the necessary human resources needed for the industry. With regards to high temperature PEM fuel cells and SOFC units, Danish companies cover the entire value chain from cell manufacturing over system design and construction to application implementation. Danish actors, as previously mentioned, have access to European grants for hydrogen fuel cell technology. According to calculations made by the Danish Partnership for Hydrogen and Fuel Cell Technology, Danish firms have historically been assigned between 7% and 10% of the total European funds given to fuel cells (The Danish Partnership for Hydrogen and Fuel Cell Technology, 2014).

4.1.7. Positive externalities

The use of hydrogen fuel cell technology has a number of inherent positive externalities for Denmark. The development of a new industry can potentially create a number of high value jobs and provide societal economic growth. European estimates indicate that there could be the need for 18,000 hydrogen fueling stations by 2050 to cover 25% of the entire car fleet, and that the price of this will be approximately €100 billion. Considering that Denmark has one of the leading European companies for hydrogen fueling station development, it is estimated that 15% of total expenditures will be placed in Denmark. This will in result give approximately €500 million exports per year and create 2000–3000 new jobs. Furthermore, the use of a domestic balancing system could make Denmark independent from foreign energy supplies and "net energy self-sufficient," as it was from 1996 to 2013, but is no more due to declining reserve-to-production ratios in Danish offshore oil and gas fields (Sovacool, 2013). Lastly, hydrogen development can reduce national greenhouse gas emissions. The Danish Energy Agency argues that hydrogen powered vehicles by 2020 could lower CO_2 emissions in the transport sector by roughly a factor of 10 compared to conventional gasoline and diesel vehicles (Cowi A/S, 2012).

4.2. Fuel cell development in the United States

The United States was the first to utilize hydrogen fuel cell technology for other purposes than research and testing. This was as part of the NASA space program in the 1950–1960s where the PEM fuel cell, which is the most widespread fuel cell technology today, was invented and developed (Fuel Cell Today, 2014). Although the technology is practically the same today, as it still uses platinum as a catalyst, there has naturally been a great improvement in performance and price.

American hydrogen fuel cell development is, due to the size of the nation, more diverse than in the Danish case, with Appendix B detailing no less than 67 major companies. Moreover, many of these feature on the list of the top 200 global hydrogen actors depicted in Appendix C. The U.S. Department of Energy has, along with a large group of industry partners, launched a new public–private partnership H_2USA with the focus on advancing hydrogen infrastructure for fuel cell vehicles (United States Department of Energy, 2013a). Furthermore, the United States is home to major fuel cell manufacturers including Bloom Energy, FuelCell Energy and ClearEdge Power (who in 2013 acquired another major actor UTC Power). Proton On-Site is an international supplier for hydrogen production technology, and the leader for integrated systems including hydrogen generation and fuel cells is Nuvera Fuel Cells (Gangi, 2013). With regards to mobility, material handling is considered a profitable niche market, with hydrogen fork lifts for indoor use as popular alternatives to battery equivalents due to larger energy capacity, which gives more work time between recharges and due to more convenient energy recharging when needed. The market leader within this technological field, Plug Power, is also headquartered in the United States.

However, though it may appear vast, most hydrogen activities are concentrated in California, Connecticut, New York, Ohio and South Carolina (United States Department of Energy, 2013a). California has historically been considered one of the most active places for hydrogen and fuel cell development, due to its politics and relatively higher energy prices. California was in 1990 the first in the world to issue a vehicle emission standard for alternative powertrains. This initiated major investments for fuel cell research and development activities by DaimlerChrysler, General Motors and Toyota. In the realm of power supply, SOFC technology gained support under the Californian Self Generation Incentive Program (SGIP). This is a program focused on reducing greenhouse gas emissions and it is recognized as one of the longest running distributed generation incentive programs in the country. It currently allocates a budget of $83 million per year of which 75% is dedicated to renewable energy technology, inclusive of fuel cells.

4.2.1. Knowledge development and diffusion

The American market features more mature and robust knowledge development and diffusion attributes. Knowledge development occurs primarily in private companies seeking to develop competitive patents. Despite being the nation spending the most in absolute terms on hydrogen and fuel cell technology, American actors are second after Japan when it comes to patent applications and number of granted patents (Fuel Cell Today, 2012). Nonetheless, they are still a major force in international hydrogen research. In 2011 U.S. actors applied for 1495 patents and were granted 841 new patents within hydrogen and fuel cell technology (Fuel Cell Today, 2012), far surpassing the activities of Denmark. Fuel cell technology has during the last ten years been the leading renewable energy technology with regards to patents, and has thus surpassed other technologies such as solar PV panels and wind turbines. According to the Clean Energy Patent Growth Index (The Cleantech Group – Heslin Rothenberg Farley & Mesiti P.C., 2014) the U.S. has 43% of all fuel cell patents globally and cumulatively the most granted patents during the last ten years. Many of these patents result from U.S. DOE programs focused on overcoming technological obstacles (Breakthrough Technologies Institute & Fuel Cells 2000, 2013).

4.2.2. Entrepreneurial experimentation

The level of experimentation with hydrogen and fuel cell systems is high in the United States, yet competitive and remarkably non-diverse. Suurs (2009) characterized it as having a minimal degree of state involvement but "highly competitive approaches to access public funds" which incentivizes distinctiveness rather than incremental change or marginal improvements to utility (Suurs, 2009). The single most important actor managing this competitive system seems to be the U.S. Department of Defense, DOD, which is focusing on the development of fuel cell units for military purposes including stationary, mobile and portable applications. Four distinct elements have been prioritized within military strategy: distributed stationary power supply, non-tactical material handling and ground support equipment, backup power supply, and unmanned air, ground and underwater vehicles (Gross et al., 2011). The visible or public experimentation of incumbent companies, however, is fairly low, perhaps because of the secrecy involved in military programs. The U.S. Department of Energy and Department of Commerce ran large hydrogen research programs in the mid to late 2000s, but these have recently been scaled back.

4.2.3. Broader influence

Hydrogen's broader social influence in the United States is mixed. On the one hand, energy prices in the United States are much lower than those in Europe due to fewer taxes, greater reliance on domestic fossil fuels, and the absence of any national feed-in tariff or price on carbon. Prices for household electricity were respectively 118.83 $/MWh in the U.S. and 383.43 $/MWh in Denmark for 2013 (International Energy Agency, 2013). This can in turn make the fuel cell technology less competitive in the U.S. in places connected to the electricity grid. The same applies for mobility applications, where the low cost of petrol can inhibit the roll out of battery electric and fuel cell electric vehicles. On the other hand, previously there have been overly ambitious political claims regarding the potential of the hydrogen and fuel cell technology (Bush, 2003), which have affected the number of actors choosing to engage in development and market creation within this technological field, generating a positive attitude towards the technology. Favorable institutional instruments have been put in place, such as the Californian SGIP mentioned above, in which a company can be compensated with 1.83$/W installed fuel cells for combined heat and power or electricity production (Database of State Incentives for Renewables and Efficiency, 2014).

4.2.4. Market formation

Despite the large amount of ongoing military research and lack of visibility, American companies are creating some new markets for hydrogen fuel cell technologies. Albeit today the markets are dependent on government subsidies, fuel cell manufacturers are very much focused on reducing cost and increasing the efficiency and lifetime of fuel cells for stationary power, material power, and hydrogen cars. There are currently more than 4500 material handling fuel cell vehicles deployed in the U.S. (United States Department of Energy, 2013a). In this regard, the United States is somewhat closer to a fully commercial market for hydrogen fuel cell technology than Denmark.

4.2.5. Legitimation

In the United States hydrogen certainly had historical legitimacy, but its primacy has weakened in recent years. Based on the historical funding provided for hydrogen fuel cell technology by the DOE, it is clear that the technology did exhibit a degree of political import. During the George W. Bush Administration fuel cell technology received significant subsidies and a vision for a future hydrogen society was laid out (U.S. Department of Energy, 2002; Bush, 2003; Sovacool and Brossmann, 2010). In 2009, however, things dramatically changed as funding was reduced drastically. Former U.S. Energy Secretary Steven Chu did not have confidence that the technology could benefit society within a reasonably short timeframe (Biello, 2009; Strickland, 2009). In 2013 DOE initiated a new public–private partnership H2USA which indicates a partial revival of support for hydrogen fuel cell technology. The goal of this is to, through collaboration, provide or establish the conditions necessary for the deployment of hydrogen vehicles (LeSage, 2013; United States Department of Energy, 2013b), though societal legitimacy is much more diverse and differentiated between individual states.

4.2.6. Resource mobilization

The mobilization of resources in the American market is certainly stronger than in Denmark, at least in aggregate terms. There is relatively high monetary resource mobilization in the U.S. Beyond the DOD and DOE programs described above, the United States is the country globally with the cumulative highest level of private venture capital going into fuel cell technology development with $815 million. The second highest on the list is the United Kingdom with less than at $320 million, and Denmark is not even included in the list of the top ten (Breakthrough Technologies Institute and Fuel Cells 2000, 2013). In 2007 the Energy Independence and Security Act also stipulated that the automotive industry reduce their average fuel consumption and improve fleet-wide fuel economy, creating incentives for both hydrogen cars as well as electric vehicles (United States Government, 2007).

4.2.7. Positive externalities

Like in Denmark, hydrogen systems have great potential to produce positive externalities throughout the United States. The DOE projects that new hydrogen and fuel cell technologies could create up to 675,000 new jobs distributed across 41 industries (United States Department of Energy, 2009). A second benefit is emissions and protection of the environment. The transition to hydrogen fuel cell vehicles has the potential to reduce CO_2 emissions considerably. According to Ruth et al. (2009), who completed a study for the National Renewable Energy Laboratory (NREL), every hydrogen production technology and configuration except for decentralized electrolysis will reduce greenhouse gas emissions. The technology is also promised as being capable of creating a more balanced and independent energy system which can enhance energy security, with the U.S. DOE (2002, p. iii) proclaiming that "hydrogen has the potential to solve two major energy challenges that confront America today: reducing dependence on petroleum imports and reducing pollution and greenhouse gas emissions" and "Its use as a major energy carrier would provide the United States with a more diversified energy infrastructure."

5. Conclusions and policy implications

This section of the paper presents three conclusions as they relate to hydrogen research strategy, efficacy of our case studies at achieving national goals, and the need for further research.

First, Denmark and the United States exhibit remarkably different TIS strategies in their approach to hydrogen fuel cell development, as Table 4 indicates. Knowledge diffusion in the Danish case is more state-centered, whereas the American case is orientated towards private actors. Entrepreneurial experimentation is mature in both cases, motivated by collaboration and driven by SMEs in Denmark, but motivated by competition and driven by larger corporations and defense contractors in the United States. Denmark sees a regulatory regime premised on high taxes and policy coordination driven by the central government, the United States sees a regime premised on low taxes and policy fragmentation with strong leadership from individual states such as California. Markets in both cases lack supporting infrastructure but leading customers in Denmark seem to be automobile owners whereas material handling, military applications, and back-up distributed generation take precedence in the United States. Denmark sees a more cogent, consistent political legitimation for hydrogen given its aggressive climate policies, whereas the political history in the United States has been more tumultuous. It is predominately universities mobilizing resources in Denmark but

Table 4
Differing hydrogen TIS in Denmark and the United States.

Function	Danish case	American case
Knowledge development and diffusion	More state involvement, most research by funding is public, fewer number of patents filed and granted	Less state involvement, most research private, greater number of filed patents
Entrepreneurial experimentation	Collaborative, mature market with largely SMEs conducting research in collaboration with knowledge institutions, fewer newer entrants, more broad ranging applications including transport, electricity, storage-balancing, and buildings, more open ended non-defensive research	Competitive, mature market with mostly large corporations conducting research, more newer entrants, more focused applications on stationary uses and cars, more closed and highly driven by the defense industry
Broader political and social influence	Higher taxes, more consistent and coordinated regulatory pressure, very aggressive government targets	Lower taxes, less consistent regulatory pressure between states, less aggressive policy targets
Market formation	Supporting infrastructure not really in place, leading customers are automobile manufacturers (for mobile applications) and home and business owners (for stationary applications), relatively small market	Supporting infrastructure not really in place, leading customers are large corporations and defense organizations, market is much larger then Denmark
Legitimation	More coherent network, very strong political acceptance for hydrogen, less robust social acceptance	Less coherent network, more inconsistent political acceptance for hydrogen
Resource mobilization	Predominately university driven research funded by national and European grants	Primarily government funded research driven by the DOD and DOE as well as private venture capital
Development of positive externalities	Improves their green image, enables spillover effects for wind energy, Denmark can potentially become a champion for hydrogen systems in Europe	Improves national image of energy security and independence, seen as a way to revitalize U.S. manufacturing

Source: Authors.

national laboratories and private companies in the United States. Positive externalities in Denmark revolve around energy storage and climate change, they center more on jobs, energy security, and industrial competitiveness for the United States.

Second, despite these differences, neither approach is particularly successful or effective. Both hydrogen sectors seem to prioritize and strategize the same thing, though they attempt to realize their goals through different pathways. The Danish and American strategies remain dually focused on performance, durability and price of technology. This coalescent strategy indicates an aim of replacing incumbent fossil-fueled power plants and vehicles with hydrogen and fuel cell technology. This may be a very difficult task to overcome considering the vested interest in the current incumbent energy system in *either* case. Despite being world leaders in hydrogen research (in per capita and absolute terms), neither country really sees hydrogen reaching commercialization and widespread use now or, if projections hold true, within the next decade.

Third, our analysis suggests the need for further research. Better conceptual models of TIS and innovation are needed—even our "modified" TIS approach does not adequately capture the intricacies and complexities of ongoing hydrogen research. The Danish and the U.S. cases are not as clearly cut, typologically speaking, as the frameworks suggested by Whitley (2000), Garud and Karnøe (2003), Spencer et al. (2005), and Sovacool (2010). It becomes clear that the Danish and the American case are similar in their collective agency, both being societal, but divergent in their research structure with Denmark being corporatist and the U.S. being more liberal. The state of hydrogen research seems to invert some classifications of development or research "style" with the Danish case being more top-down (driven by government) and the American case more bottom-up (driven by the private sector). American researchers are actively engaged in commercializing the current available proven technology and Danish actors are striving to make the technology competitive before commercialization. On the other hand the Danish companies have a major advantage in the openness in the network centered in the Danish Partnership for Hydrogen and Fuel Cells, which means that Danish actors and stakeholders are collaborating in the entire value chain and interacting with the institutions in order to increase the chance of establishing what by some actors have been called "the new windmill adventure" for Denmark. The implication is that the specificities of hydrogen research in both cases are more complex, and less predictable, than what existing theories of innovation and structure imply. As such, some of the fundamental assumptions underlying TIS and similar theoretical concepts may need rethought.

Appendix A. Supplementary material

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jclepro.2015.01.056.

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