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Technology development and strategy

- an exploration of automotive fuel cell technology.

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Abstract

Development of technology is related to several considerations and is not reserved for R&D facilities, because corporate boardrooms and governmental institutions are also involved in technology development. The field of strategy has been somewhat neglected in the literature about technological development, but is considered a cornerstone in this dissertation. Automotive fuel cell technology and its development towards market introduction is the focus of this paper. Fuel cell vehicles face competition from an established technology, the internal combustion engine, which can be considered to be in a lock-in situation. A lock-in is different than competing standards, as differences between technologies goes deeper. Established technologies often evolve and adapt to society for decades, and gain cumulative advantages and become "locked-in". A set of necessary and enabling conditions to escape the lock-in is presented, to show how technological change can be promoted.

To create a technological nexus consistent of companies, institutions, R&D facilities which gives the technology strength is chosen as a strategy to overcome the lock-in. The use of strategic technology alliances to create the technological nexus is considered, and how alliances can be used to gain power and influence within the nexus is also an important question in this paper. The discussion on the use of alliances has its main focus on the alliance between Ballard Power Systems, DaimlerChrysler, Ford and their three joint ventures. The General Motors and Toyota cooperation and the PSA Peugeot Citroen alliance are also outlined, to illustrate the different approaches taken by different companies. The notion arenas of development is used as a theoretical framework along with strategy to cast light on technological succession, this combination was chosen because AoD have the strength to enhance the field of strategy regarding development of new technology.

The strategy of creating a nexus seems useful for technological development in overcoming the obstacles related to the lock-in on the internal combustion engine. The strategy of creating a nexus did not contradict the strategy of gaining power in the nexus. On the contrary, a strategy of creating a technological nexus was compatible with gaining power inside the nexus in the approach taken by the Ballard Power Systems, DaimlerChrysler and Ford alliance.

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1. Introduction

Focus of the paper

There are several interesting aspects to strategy and technology, and development of new technology is selected for further investigation. The random and unpredictable process of innovation is often emphasised in the ESST programme. A strategic perspective on technology development is chosen, because fuel cell vehicles are not likely to surprisingly emerge by random events and strategy is an important aspect of the process towards a potential market introduction.

The phases of development and processes towards commercialisation of automotive fuel cell technology are about to be explored. The fuel cell technology faces difficulties related to the lock-in phenomenon on the internal combustion vehicle. An important aspect of this paper is how alliances can be used to overcome a lock-in on a technology. The development of a technological nexus is considered a strategy for technology replacement and is of central importance in this paper. How strategic alliances can help create a technological nexus and overcome the obstacles related to the lock-in is an important question. How alliances can be used to gain influence and control within the technological nexus will be discussed. After the theoretical paper, the points mentioned in this paragraph will be discussed in the following three chapters.

In chapter three, the focus is on cars and the lock-in on internal combustion vehicles (ICV[1]). I begin with a discussion on historical reasons for the lock-in and show how the process gradually reinforced the strength of the ICV. The main part of this chapter is devoted to discussing the necessary and enabling conditions for escaping a lock-in failure. The chapter ends with a presentation of an integrated set of necessary and enabling conditions for escaping a lock-in failure.

[1] Abbreviations and acronyms are used, and will be spelled out the first time they are used, however Appendix A lists all the abbreviations used in this paper.

The fourth chapter discusses the automotive fuel cell arenas of development and how strategic technology alliances have been used to build and strengthen a technological nexus. Strategic use of alliances to gain power and influence in the technological nexus is also discussed. Specific focus is put on the DaimlerChrysler, Ford and Ballard Power Systems alliance and on the significance of partial connections in creation of the technological nexus.

The contributions from the two former chapters are taken into discussion in chapter five. How a technological nexus can embark upon the conditions related to the lock-in is the first major point. The secondary point in this chapter is how strategic alliances can be used to control the technological nexus in favour of specific actors, in relation to the necessary and enabling conditions for escaping the lock-in failure. Again, the focus is on the BPS, DaimlerChrysler and Ford alliance.

Three appendices appear in this dissertation. Methodological aspects of this paper are discussed in appendix a. Appendix b is a list of acronyms and abbreviations that have been used. The last appendix lists a variety of actors involved with fuel cell development in to illustrate the amount of actors involved in the technological nexus for automotive fuel cells, not discussed elsewhere in this paper.

2. Theoretical approaches

The use of theory is an important factor whenever one tries to comprehend the world. A theory provides a framework of understanding the world as it highlights some aspects of reality at the same time as it downplays other parts. The world of technology and alliances are complex issues, and rigid theoretical framework is not the best solution for handling it. Like Løvendahl & Revang (1998), I believe that the grand universal theories of the firm are losing their value in explaining how firms should operate. The ANT framework is unrestrained enough to describe agreements and alliances in the economic sphere without being bound up by theoretical limitations (Lee & Hassard 1999:394). AoD (arenas of development) is unrestrained in the same way as ANT (Actor Network Theory), and provides a theoretical framework for this dissertation.

Strategy is an important aspect of this paper. Alongside AoD, strategic discussions will complement and provide additional insights into the development of new technology. A discussion on how to replace old technology with new technology is important. Technology substitution is important for companies and society in general, thus it needs to be explored further. AoD can act well as a tool to understand strategy and technology, because it does not neglect the multifaceted complexity of technological substitution and is at the same time open for an understanding of strategy.

Arenas of Development

An arena of development (AoD) is a theoretical notion used to understand development of new technology. It has similarities with theories like ANT and technological trajectories. ANT is the theory considered being most similar to AoD. Aspects of ANT will be used to complement the understanding of technological development in this paper, as only two articles have been written on AoD[2]. The notion is considered useful to deal with topics that fall outside of regular economy and management literature (Jørgensen & Sørensen 1999:410-411). It is capable to shed light on automobile fuel cell development, which is a special case that to some extent falls outside the mainstream frameworks. AoD and ANT have the potential of providing interesting framework for strategic considerations in the FCV arenas.

AoD can be defined as a cognitive space that includes a wide variety of actors (defined later) and intermediaries (defined later) involved in technological development. Standards, companies, technologies, governments and other institutions can be actors and intermediaries. Geographical positioning, expertise and company (as well as personal) visions can play vital parts in AoDs. A number of translations (defined later) also play an important part in influencing and stabilising the arenas of development (ibid).

A significant point in AoD is the partial connection between different arenas. It ensures that development in one arena might easily influence other arenas. A major technological breakthrough in one arena is bound to influence the other arenas involved with the same or partially connected technologies (ibid). In this respect the notion of AoD is more interesting than ANT, because it points to a certain interrelation between networks which always have the potential of emerging.

The arenas will remain changing as long as the technology or product is not stabilised. (ibid) Customers, markets and organisational forms depend partially on the stabilisation of the technology. Technical, social, cultural as well as political influence can play important parts in the development of new technology. Generally speaking, the arenas can be easily entered before the technology is stabilised.

[2] Those two articles are; Jørgensen & Sørensen (1999), and Sørensen (1999).

Many theories have a focus on technology, but AoD distinguishes itself. Theories about path dependence and technological trajectories focus on the dominating power of the existing technology. AoD on the other side focuses on how new technologies emerge and diffuses. Even though AoD embraces concepts like trajectories and paradigms, its focus is on how new technology is able to emerge (ibid: 416). In contrast to the many theories that emphasise the dominance of existing technologies, and how and why existing technologies will stay dominating.

Actor Network Theory

The early writings on ANT of relevance to this paper, as complementary to AoD. The most important and useful notions will be presented as straightforward as possible, to increase understanding of later discussions[3].

To start chronologically one can say that ANT started out with semiotics. In accordance with semiotics, objects had no significance in itself, but achieved it through relations with other parts (Law1999: 3-9). In following such a belief, ANT was able to bypass controversies between social and natural divides, as well as other controversies. ANT does not deny distinctions or differences per se, but sees them as a result of relations and not characteristics (ibid). ANT was at the same time related to performance, because important issues rose from how entities performed in relations, and how performances in relations could evolve to stable entities. Relations can already be connected, or be performed into a relationship (ibid).

The further presentation of ANT will begin with describing its view of the world through the notion of techno-economic networks, to continue with actors and networks, and end with the process of translation.

[3] From a relatively straightforward framework, ANT changed into complex theory. For the interested: "Actor Network Theory and after" (in Law & Hassard eds.1999) presents some of the vastly different directions in ANT.

Techno-economic network

The notion of a techno-economic network is explained trough Callon's (1991: 133-142) article. A techno-economic network (TEN) is a notion to understand the phenomenon of technological change; Callon describes it as a set of co-ordinated actors that interact in relation to new technology. TEN is seen as having three dimensions: scientific, technical and market. The three poles are partially separate and partially connected and interact with each other by intermediaries. The three poles can mutually shape and direct new technologies through the already mentioned intermediaries. An intermediary can be defined as "anything passing between actors which defines the relationship between them". There exist four kinds of intermediaries:

- *Literary inscriptions*: usually texts which plays a significant part in the development of science.

- *Technical artefacts*: measurement devices and other non-humans that play a part in connecting actors. Technical artefacts are not remote creatures, but include a mixture of social and scientific factors. Interaction with user demands can be seen to have effects on actors with regard to questions surrounding an artefact.

- *Human beings*: human abilities and knowledge also plays a part in connecting actors, skills are both social and technical, and can include non-humans into the network.

- *Money*: money and other kinds of payment can support actors' relations. Money interacts in relationship between actors and can be translated to different things.

I have described the three different poles and intermediaries that connect them, but the notions of actor and network in ANT have not been properly addressed yet, so I will approach these notions now.

Actors, networks and translation

An actor is an intermediary, which has the possibility of building a network, through being able to connect or activate different kinds of intermediaries in a way that suits the actor's interest. The actor can be an individual, a company, materials, a machine, non-humans and emerging technology. The distinction between an actor and an intermediary is rather flexible. Actors can be intermediaries and intermediaries can be actors, however the difference can be seen as the actor has "authorship" for getting the intermediaries to act, while the opposite is not true (ibid).

A network consists of all actors and intermediaries involved in the relevant task. An actor is also a network in the sense that they are defining each other in terms of agreements reached through translation (Callon 1991: 142-143), which will be discussed soon. The network will always be under pressure to change, and different actors and intermediaries have the power to change it. Networks should not be perceived as stable because they need to be constantly confirmed. Hidden agendas and conflicting interests ensure difficulties in confirming a network. Callon (1991: 150-151) proposes that network stability increases with the number of relations and the heterogeneity of the relationships in the network. As norms and values are accumulated, the network gains more resistance to opposing networks or arenas. Implications are that time, trust and heterogeneous actors are factors favouring the strength of a network.

Translation is a wide term, which encapsulates several matters. All matters are seen to have four stages. The most important reason for the naming is that it does not interfere with common vocabulary of actors and intermediaries. Network translations can be seen as defining other actors or intermediaries, so the translator can be said to define the other part(s). A translation must necessarily involve three parts: a translator, an intermediary in which the translation takes action and someone or something to be translated (ibid: 143).

The four sequences of translation

1. *Problematisation*: this stage regards identifying and mapping the key players and to involve them by convincing them that the solution to the problem can be found by dealing with that actor.

2. *Interessement*: existing networks may be responsible for hardship for new networks. The translator can gain by trying to dissolve the existing network before and while the new network is evolving.
3. *Enrolment*: trying to achieve a stable identity for the network through all means available, be it force, persuasion or voluntary agreements. Strategic alliances are one possible way of enrolment.
4. *Mobilisation*: mobilisation is about the entities involved in the network and trying to get them to "mobilise" or speak for a larger part of the actor-world.

(Callon 1986: 196-203 & Grint & Woolgar 1997: 28-32)

An important aspect of translation is the notion of "obligatory passage point" or OPP. It is by itself a necessary condition for solving a specific situation. The OPP is a key position to the solution for the problem, so other actors need to involve it; hence its strategic value. Problematisation is about letting others believe that the solution can be found through the translating actor. OPP differs because it involves being in a position that ensures a key position for negotiating the solution. (Callon 1986: 196-203)

The OPP and the notion "centre of translation" have some similarities, but also some differences. The centre of translation is the actor/arena that manages to translate other actors, that is, it has control or influence over other actors. The OPP is the actor or intermediary that is a key point or enabling factor in the arena. But while the centre of translation necessarily will be an actor, the OPP might just as well be an intermediary. The OPP having the possibility of being an intermediary signifies that other actors can enrol it into the network. The centre of translation can enrol the OPP that can accept or refuse to be enrolled into the network.

Strategy

The word or concept of strategy has several meanings, and is equally confusing or insightful-depending on the reader. The field of strategy must remain black-boxed, even though it is one of my main approaches in this paper. In the fields of strategy, there are 10 different schools[4], and there is obviously no room for presenting all these theoretical approaches in this paper.

Three of the schools can be characterised as prescriptive and based on ideas on Homo Economicus. Some schools are occupied with external pressures while other are engaged with internal pressures and some on the actual making of strategy. If one look at Habermas (1972 in Booth 1998: 258) one can distinguish among three modes of knowledge production: 1) Empirical-analytical, 2) Historical - hermeneutic and 3) Critical science. The differing modes of knowledge production in the field of strategy can be seen as different knowledge paradigms, and as Booth concludes, they are incommensurable. So there is no general point of reference in the field of strategy, which would make it demanding and space requiring presenting the field much further. However, AoD and ANT's characteristics give the opportunity to bypass the differing knowledge paradigms.

The mainstream definition of strategy is often connected to ideas of rationality and a "Homo Economicus" point of view. I do not intend to use the mainstream definition, because it is connected with an idea about a predictable future. Random events play a large part (Arthur 1988) in technological successions and lock-in failures; hence, the rational approach is not suited for discussions about technological successions.

Strategy is important because management of fuel cell R&D is strategic by nature[5] (Steinemann 1999: 23). Since fuel cell R&D is recognised as important, it should have a thorough evaluation of both organisational intent and socio-technical circumstances. A usual strategy for alternate propulsion technology is development of several technologies being developed into a portfolio of technologies. Lack of knowledge, and fear of developing the "wrong" technology are risks for companies (ibid:10). Many car companies have followed the just mentioned strategy, and involved themselves with different kinds of cars, EVs, hybrids

[4] Mintzberg (1998) operates with 10 different schools, while Lewin & Volberda (1999) operate with 12 different schools of strategy, the main point being the multitude of approaches to strategy.

and FCVs. It is interesting to note that the focus as well as the cash flow has changed in the favour of fuel cell technology in the last few years.

I will use a rather wide definition of strategy known as the five Ps of strategy (Mintzberg 1987 in Mintzberg 1998: 9-15), which actually are five definitions of strategy. The five Ps of strategy consist of strategy as:

- Plan
- Pattern
- Position
- Perspective
- Ploy

Strategy as *planning* can be considered as the making of guides or paths of how to behave in certain situations. Strategy as *patter*n is quite different from the previously mentioned "P", because it views strategy as emerging bit by bit, contradictory to actions planned a long time in advance. According to this view good strategies evolve within learning, routines or culture of the firm. *Position* as strategy is linked to finding a position in which one can compete efficiently. Positioning is associated with Michael Porter (1980), but used in a bit wider context here and is not limited to his generic strategies. *Perspective* is (Drucker 1970 in Mintzberg 1998) the organisations "theory of business", or how the business unit perceives the business environment. The perspective of an organisation is a major shaping factor within the organisation and affects choices and actions done, and that notion is relatively similar to the notion of culture in organisations. A *ploy* is a move towards a specific goal or target, and have a shorter time horizon than the other aspects of strategy.

Different schools of strategy are biased towards differing P's, and this paper uses certain P's more than others as well. All the P's will be considered as what they are: partial explanations or definitions of strategy, all having their differing contributions, which will be put to use whenever it is suitable. With use of ANT, "positioning" becomes important, as a reflection on the importance of positioning within a network. "Ploy" is used to describe enrolment, and is important in network approaches. "Pattern" is used to understand the emerging character of

[5] Whether or not its significance is natural or social in not of relevance, but it should be considered important.

strategy and technological development. Strategy as a “perspective” and cultural element is not in the field of my investigation, and not addressed in this paper.

The use of five definitions of strategy, and some other notions (defined at use) seem a bit complex. One can question the compatibility between the different strategic approaches, and additionally the compatibility with AoD and ANT. The problems of compatibility are acknowledged but: “Every strategy process has to combine various aspects of the different schools.” (Mintzberg 1998: 367). To make all aspects of strategy compatible with AoD and ANT is not advisable, because it would impair the understanding of technological development. Hence, the conflicting theoretical aspects are evaded.

Strategic alliances

There is no room in this paper for a thorough review on literature on strategic technology alliances, but I will give a brief introduction of the logic behind alliances.

Strategic alliances can be defined as two or more organisations joined in a mutual agreement, without affecting the exterior of the company (Oxford Business 1996). This definition is narrow and has some problems since the term “alliance” is not a single configuration, but exists in several versions. A taxonomy about partnerships has not been fully developed and there is confusion about the naming (Hagedoorn et al. 2000: 568). However, Maruo (2000: 41-42) identifies seven kinds of alliances: mergers, acquisitions, strategic shareholding, joint ventures, national R&D partnerships, limited strategic partnerships and intergovernmental cooperation. There are many possible alliance configurations, but there is no room for providing explanations of them.

Other terminology describing the same issues can be referred to as inter-firm agreements, R&D consortia, co-operative agreements, strategic alliances, strategic technical alliances as well as other options. I choose not to enter the taxonomic discussion of alliances, but use alliances as a wide term and try to be precise in my formulations so the reader will understand what kind of alliance I am referring to.

The logic behind alliances (Doz & Hamel 1998:1-46)

- *Co-option*: to make other companies enter collaboration instead of competition.
- *Co-specialisation*: to make use of existing capabilities within several companies, with the belief that synergies[6] will occur, enabling companies' greater achievements.
- *Learning and internalisation*: the possibility of learning by doing in collaboration with other organisations.
- *Critical mass*: the belief that being able to produce a higher number of units allows the organisation to receive economics of scale and be able to influence standards.
- *New markets*: alliances can be used to allow companies to enter new geographical areas.
- *Skill gaps*: alliances can cover the different partners lacking capabilities, and together with learning it may expand company's development and production capabilities.

Alliances that are focused on technology development have some additional reasons for joining alliances (Tidd et al. 1998:198).

- *Cost reduction*: technological development and market entry are increasingly expensive and collaboration is generally expected to reduce costs.
- *Risk reduction*: as risk can be very high, having collaborating partners are often perceived as reducing risk.
- *Product development time*: development time and commercialisation time is expected to be lower when partners are joining their efforts.

If one considers all these reasons, one can grasp the main reasons why companies enter alliances. Creation of networks is often a good solution in technology development, and networking is often seen as a viable innovation strategy by itself (Harris et al. 2000: 238). It may seem a little naive to think that innovation is ensured if cooperation takes place, because there are other important factors, but there is a strategic importance to collaboration.
Companies may also have more situational and specific reasons for entering alliances. Alliances for development and substitution of a technology may have specific reasons for

[6] When the results of the alliance are more than the companies could have managed by themselves (Oxford: Dictionary of Business 1996).

entering alliances. Specific reasons for entering FCV (fuel cell vehicle) alliances will be explored later.

Strategies for inducing technological change

Inducing technological change or escaping a lock-in failure are hard, however three major strategies have been identified (Schot et al. 1994: 1064). They are originally treated from a government (policy) perspective, but are useful for alliance strategy.

- Pronunciation and expression of expectations, beliefs and wishes that might change the view on either an emerging technology or the established technology.
- The creation of a technological nexus, which connects and partially controls the development of new technology.
- Strategic niche management; the idea of letting a technology develop in a protected space so that it can evolve without the standard market demands, and later enter the open market.

While the three strategies can be useful, and often complementary, there is not enough space in my paper for a discussion on all of them. Both strategic niche management and expression might be important for the development of fuel cell cars and their market entry. But, the focus will be on the creation of a technological nexus and how strategic technology alliances can contribute and influence it. In this way technology alliances is understood as more than joint R&D and includes ways which the alliance can influence its surroundings. The notion of a technological nexus is in many ways similar to that of a techno-economic network. The technological nexus will be considered to consist of the same three dimensions as the techno-economic network.

Twining strategy and AoD

A good reason for twining strategy and AoD is that management of innovation can be considered the same as entering an arena of development, in which strategy is an important issue (Jørgensen & Sørensen 1999:418). AoD is fruitful for understanding product and technology development for management and strategy. It removes management from narrow confines and can enable management practice to understand the more complex relations involved in technology development. Even though alliances are already popular, AoD cast a new light on trade-offs concerning competition and cooperation (ibid: 425).

As many areas of strategy have rejected the image of rationality, the social character of strategy has become more important. Strategy can be considered as instruments for understanding the environment. As issues of power and "authorship" have entered Strategy[7] and AoD, these scholarly directions have become more overlapping (Coombs 1995: 339). Networks have had increasing interest in strategy, therefore the similarities and compatibility between the theories have increased even more.

Both theories are dependent on other actors to act in their interests. Actors in ANT, and colleges or business associates in strategy can have positive or negative influence on maintaining a network. Neither technology nor strategy can be stabilised without backing from the network, therefore social impact and interpretation can play parts in both theoretical fields. Strategy and technology development are interrelated, strategy is an intermediary in the network of the technology being developed. At the same time can the technology in development be an intermediary or part of a strategy (ibid).

The strategy proposed by Schot (et al. 1994) of succeeding a new technology through development of a technological nexus, can be understood as a gathering of forces of technological understanding, which is strong enough to promote and develop the technology. If strong organisations push a technology, and other actors adopt it, then it seems like the technology has forces of its own. Increasing returns to adaptation (will be discussed later) is a social phenomenon just as much as a technical phenomenon. By developing a technology that

[7] Not all fields of strategy, but some fields within strategy have entered into discussions about power and "authorship", and can be said to have similarities with ANT.

acquires a certain power or push, it gets the ability to set standards and can become a technological nexus. A technological nexus can be considered to have the same three dimensions as a techno-economic network, and the two concepts are relatively similar. Therefore the technological nexus is considered to have a scientific, technical and social dimensions attached to it. The importance of institutions in the development of new technology have also been emphasised by Granovetter (1985) and Nelson (1994) (both in Larbaoui 2000:2). Granovetter states that institutions play a part in the dynamics of technology diffusion and economic calculations concerning the new technology. Diffusion of this kind of knowledge makes it easier for other companies to get involved with the technology. There are no apparent reasons why the kind of just mentioned dynamics should not apply to automotive fuel cell technology, so creating a technological nexus could play a very important part of fuel cell development. In dealing with magnitudes of actors and arenas AoD is a useful theoretical framework, and FCV development makes no exception.

Together all the different arenas of development can be considered a technological nexus. The BPS, DaimlerChrysler and Ford alliance, the Toyota-GM cooperation, Honda, several research institutions and first tier suppliers like Delphi can be considered a nexus since it involves several heterogeneous actors. The involvement of governments and NGOs also play parts in strengthening the technological nexus.

Translation can be considered similar to the process as creating a technological nexus. Both processes include incorporating new members and building up support, for a strategy or a technology. As enrolment was defined as increasing and stabilising a network, trough any means. There is no reason why alliances of other business agreements should not be considered enrolment. The four phases of translation can be considered to be the equivalent (or close) to the use of ploy in strategy. Enrolment can easily be considered a ploy, but the building of a network has a longer time perspective than a ploy.

Controlling a technological nexus has much in common with becoming the centre of translation. Alliances can be considered a way of enrolling new actors, and get them to support the actors intentions. Viewing the centre of translation as a controlling actor within the technological nexus is also plausible. The centre of translation has “authorship” of action and context in the nexus, and is the central actor.

The OPP plays an important part in the nexus. As the OPP is a necessary key to the solution, enrolment of the OPP is of importance. Enrolment of the OPP is a key issue whether one calls it enrolment or a ploy. Securing the OPP could be called obtaining a strategic position in the environment, or simply enrolment of the OPP. However, as the OPP can be a key to both strategy and technology development, it is of central importance.

A caveat on strategy and technology development

It should be emphasised that technological development can only be partially controlled by strategic intent[8], because there are numerous possibilities outside control that might influence technological development. The technological nexus is more than one arena, and consists of all the arenas of development, of which the "Alliance" is only one actor. In HDTV development new actors emerged and transformed all the arenas of development in that technology (Jørgensen & Sørensen1999) and the strategic intent of the arenas involved hardly mattered. A sudden transformation of the AoDs cannot be denied totally in fuel cell technology either. Competing alternative propulsion technologies like pure electric cars might roar if radical improvements are achieved in battery technology, leaving fuel cell technology obsolete. Cooperating actors may abandon the belief in a technology, as well as other actors resisting the translations of the lead actors. Creativity enhancing software may also play a part in technology development and be an actor/intermediary who changes the arenas of development as well (Gagnon 1999:101). It is hard to determine the level of intent possible in shaping a technology with all the influencing factors, before the technology is developed and have been around for a while. That actors will try to influence technological development and processes towards market introduction is quite certain as the investments and outcomes can be very high. With creativity and knowledgeable heterogeneous engineering some amount of strategic intent may be implemented (Law 1992 in Sørensen 1999: 30).

After the conditions necessary for technological succession are discussed, the focus will change to how and why strategic technology alliances as centres of translation can control a technological nexus and achieve and fulfil the conditions necessary for escaping a lock-in failure.

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[8] Strategic intent can be defined as: a desirable goal to pursue, which is accompanied by appropriate means and a sense of direction and importance for an organisation. (Hamel & Prahalad 1996: 141- 158).

3. Necessary conditions for going beyond a lock-in

This chapter is centred around the lock-in on the ICV and alternatives for escaping it. First a lock-in will be defined and the process of lock-in on the ICV will be considered. Alternatives to the ICVs will be discussed before the necessary and enabling conditions to escape a lock-in is discussed. At the end of the chapter, an integrated set of necessary and enabling conditions for escaping a lock-in failure is presented.

What is a lock-in?

A lock-in can be considered the processes that make a technology dominating in its sphere. A lock-in can be defined as the situation after a technology has managed to gain market dominance, and has strengthened its competitive advantages through years or decades of learning (Cowan & Hulten 1996:61).

Random events are often given as reasons why one of competing technologies becomes locked in (Arthur 1988). Random events can reinforce the technological choice through increasing returns to adaptation. It is the response that follows a market leadership that locks in a technology. When the personal cost of switching technology becomes to high for most consumers/users, the lock-in phenomenon has started its effects[9] (Cowan & Hulten 1996:64-65). When a technology is gaining popularity through lock-in, the process reinforces itself. As more people get connected the more the technology will be improved, and as it improves more people get connected (Arthur 1988)

When the technology has received increasing returns for a while it often starts co-evolving with social and cultural demands, and supporting institutions are often developed. As an overall result one can say that the technology has become “locked-in”.

The lock-in on the ICV

[9] This must be considered the “easy” version of increasing returns to adoption; a more thorough explanation is given later in this chapter.

At first the historical developments that picked out the ICV (internal combustion vehicle) as the major propulsion technology for cars will be considered. The ICV was not the only or obvious choice as a propulsion technology. Cars driven by steam and electricity were highly competitive with the gasoline driven car at the end of the nineteenth and in the beginning of the twentieth century. In 1895 gasoline cars were seen as the inferior option of the three categories of cars (Arthur 1988). The competitiveness of steam and electricity cars can be seen in the number of sold cars. In 1899 1575 electric vehicles, 1681 steam driven cars and only 936 gasoline cars were sold (Cowan & Hulten 1996: 66). The numbers show that the ICV was the least sold car that year which tells us that there was nothing evident about its success.

Brief sketches of the different car's development follow, besides a short description of the competition and factors leading to the lock-in on the internal combustion engine (ICE).
The steam driven car was developed during the period 1860-1890 and was produced mainly in France and USA. The car's main advantages compared to ICV were less moving parts hence more flexibility and less dependency on exact endurance conditions. In addition it could not stall and had easier operational gear system and was easy to manufacture. The downside with the steam car was high energy loss due to low thermal efficiency and mechanical faults due to high pressure along with requiring large amounts of water and requiring the same amount of gas as ICVs (Flink 1988: 6-7).

The electric vehicle (EV) was quite popular in USA, and a best seller for a while. Lack of noise and smell and it was rather easy to control, were its advantages. The upper classes viewed it as a fashionable and conservative car. A disadvantage, now as than, was the car's relatively short range of and lack of access to recharging the batteries. The heavy weight of the battery gave the car problems in climbing steep hills (ibid: 8-10).

The ICV was developed and improved in France and Germany, while UK and USA were lagging at least a decade behind. The development of Nicolaus Otto's four-cycle engine ended up in a patent lawsuit that made the engine public domain. With quick diffusion of other key innovations in the ICV also contributed to a relatively rapid development. Its main advantage was the long travelling distance, and (after some years) its price, while a relatively rough drive and especially tough starting procedure were its disadvantages (ibid: 10-14).

The automobile competition started in the 1890s on the European continent while USA was lagging behind. In 1899, the electric car seemed most advanced, as the ”La Jamais Contente” was the first car ever to reach the speed 100 km/h. In the same year the Electric Vehicle Company bought the Selden patent, a crucial patent for the ICV. The change of focus of one of the biggest EV manufacturers, somewhat foreshadowed the change of EV manufacturers and key people becoming occupied with ICV. The sales of EVs doubled in the period between 1899-1999, but ICV sales multiplied 120 times in the same period (Cowan & Hulten 1996: 65-67) giving the ICV configuration considerable increasing returns to adoption.

Production, marketing and the technical reasons contributed in the ICV upswing . ICVs were mass-produced from 1901 and sold at a lower price than the competing car configurations. ICVs were marketed to a large population when the EV and steam driven manufacturers preferred to sell to the upper classes (ibid). The just mentioned elements contributed to a large escalation of ICV production while EVs and steam driven cars steadily became a smaller percentage of the car population. The mass production of the ICV was reflected in its price, and helped it gain further advantages. In 1913 Ford T-model cost 600$ while an EV cost 2800$ that year (Freeman & Soete 1997: 141). Arthur (1988) points out other small random events, which cumulated into doing a difference.

After the initial and partly random selection/victory of the ICV, increasing returns to adoption occurred and continuously reinforced the ICV position in society contributing to its lock-in. In the following decades, ICVs became ever more embedded in society, it started influencing social life and was developed further in co-evolution with society. The numbers of ICVs in societies increased, and so did their co-evolution with society. The ICV became increasingly “locked –in” as a technology.

A century of improvements along the dimensions of reliability, speed, endurance and fuel efficiency as well as design and materials has improved the ICV significantly.

The auto industry with few new actors, because it is capital intensive, has made changes harder. The car is also part of a larger technical system, with roads, educational facilities and repair shops. The infrastructure has also accumulated advantages over decades that are hard and costly to replace. The ICV has also entered people’s personal lives and affected the organisation of everyday life (Kemp 1994) in such a way that changes in the car configuration would require changes in social and individual lives. Such a requirement is hard because the cultural and social power of the car have had much impact on everyday life. As an example, the vast expansion of ICVs has favoured individual transportation, and made it hard to make collective modes of transportation economically viable. In this way the ICV imports have brought some of the American individualistic culture into other regions and limited other options for transport.

Another limitation for new technologies to emerge is that prior technology decisions play a part in deciding future decisions. Lock-in on core capabilities[10], and certain ways of acting, favour existing technology and set new emerging technologies at a drawback (Unruh 2000: 821). The capabilities in the car industry reinforce the ICV solution. A FCV requires competence in electrochemistry, electro catalysis and chemical fuel processing. Those knowledge bases have not been strongly represented among ICV manufacturer's capabilities (Steinemann 1999:6).

Why is it so hard to escape a lock-in failure?

Escaping a lock-in failure is hard and deserves explicit attention, although it has been implied in the previous paragraphs. The co-evolution of the ICV and the environment has significant implications as billions of US$ are spent on the ICV infrastructure globally. The car configuration have evolved together with user demands, and made the characteristics of the car a social and technical mixture. Speed and range of the ICV have come to be “the important” characteristics of the car, which puts other technologies at a drawback (Kemp 1994).

The impact of the ICV on the Norwegian society is a good example of the interrelated technical and social effects. The ICV played an important part in changing Norway (Sørensen 1991 in Kemp 1998:335) as with other developed countries. Mobility increased, and it became synonymous with personal freedom and became part of everyday life. Norwegian

[10] Core capabilities can be considered a company’s competitive advantage and consist of specific knowledge and competences that separate them from other companies (Leonard 1998: 1-28).

authorities imported American perspectives in the planning and administration of public affairs, in relation to infrastructure and other issues. Professional training of engineers and mechanics facilitated the ICV lock-in. As time went by, local establishment and individuals had higher demands to adaptation of regular life to the automobile. When large parts of the general population is involved with making society adapt to the ICV it will be hard to make changes. A good example of parts of society demanding that society must adjust to ICV could be seen across Europe in September 2000. Several European countries are experiencing civil disobedience in relation to the price of gasoline and diesel. Transport workers are demanding governments to make changes concerning the price. The ICV is a techno-economic network that is huge and powerful on all dimensions, which should not be underestimated if trying to escape the ICV lock-in. Unions have also been known to identify and support the demands of a locked-in technology after years of co-evolution (Galbraith 1967 in Unruh 2000: 824). In Norway one of the two transport workers unions was involved with illegal protests towards the tax level on diesel and gasoline, which exemplifies the power of the ICV network.

ICV infrastructure built up by roads, signs, laws, public, and private actors who are supposed to serve the ICV demands. These actors may not be well suited for addressing alternative propulsion demands (Unruh 2000:819) as they might be adjusted to the ICV network. As timetables for institutional change are slow and formal institutions usually change over decades and informal institutions need even longer (Williamson 1997 in Unruh 2000: 824) it becomes apparent that escaping a lock-in failure is hard.

The basis for financing a technology can also reinforce the embedded technology (Unruh 2000: 823). Profits made on a technology and its product usually goes back into the technology for further development of it. The same tendencies can often be found in financial institutions, which often are risk averse when it comes to supporting new and radical technology.

It is not impossible to escape a lock-in, but there are several obstacles. How it can be done, and necessary conditions for it will be discussed later.

Alternatives to the ICV

After the alternative car engines almost disappeared in the beginning of the twentieth century, the issues resurfaced in the face of an environmental and energy crisis in the 1960‘s and even more with the oil crisis in 1973. The oil and energy crisis led to searches for alternative technologies with an environmental profile (Perez & Soete 1988 in Larbaoui 2000: 1). A brief sketch of some of these possibilities follows, and I will try to clarify the naming of these cars. As different authors have used different taxonomies for the same cars, creating confusion.

Electric vehicles

Although the idea of a steam driven car has disappeared, the idea of EVs had a relatively strong comeback and has been available for some years. In the upstart relatively small and new companies started producing EVs, while in the latter years the big manufacturers have taken over. Larbaoui (2000) shows a declining utility market share for Seer Volta while Renault, Peugeot and Citroen establish themselves as bigger actors. In 1995, the big French actors released electric version of these cars: Peugeot 106, Citroen AX, Renault Clio and the express Renault (Larbaoui 2000: 9). Ford is also involved in electric cars, with its recent “Think”, showing that the large global players are involved with EVs. They are generally considered ineffective compared to fuel cell cars. For that reason, EVs is often considered as a temporary product, to be replaced by FCVs (Buen et al. 1999).

On the EV terminology there is some confusion, usually regarding whether FCVs should be considered EVs. Some include fuel cell driven cars as EVs since the fuel cells are use to power an electric engine that makes them partly electric. I prefer to exclude fuel cell driven cars and include cars with only an electric engine when I talk about electrical cars or EVs.

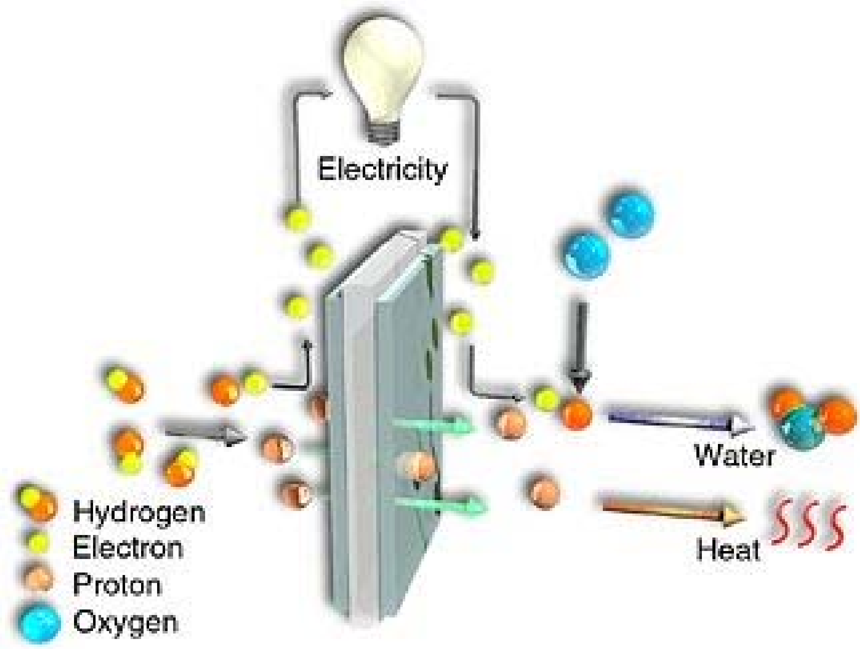
Hybrid cars

Hybrid cars come with different configurations. The most traditional hybrid, if such a thing can be traditional, is the hybrid with an internal combustion engine as well as an electric engine. This configuration uses the electric engine during city and low speed driving, while the ICE works during high speed driving as well as long distances.

Toyota Prius was the first hybrid car to be mass-produced, with a market arrival in Japan in late 1997, with supposedly good sales. Toyota does not expect to break even for some time because of the extra cost of having two power supplies (Eisenstein 2000). It will of course be hard to make a profit when the cost of producing the car amounts to 40 000 US$, while it is sold at 20 000 US$, however the Japanese state is subsidising 8 000$ pr. car. As for the naming of this car, I will refer to it simply as a hybrid car, or simply HEV from hybrid electric vehicle.

Fuel cell cars

Fuel cell cars run on electric engines powered by fuel cell stacks. Fuel cells are electrochemical artefacts that use chemical energy and transform it to electric energy stacks, fuel cells stacks (Srinivasan 1999: 284 – 287). The following illustration show how fuel cells produce electricity:



(Plugpower 2000)

There are different kind of fuel cells, I will limit myself to saying that PEMFC is the kind of fuel cell currently looking as the best alternative for cars, and what most car manufacturers are looking into[11].

[11] The Proton Exchange Membrane Fuel Cells (PEMFC), Direct Methanol Fuel Cells (DMFC), Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten-Carbonate Fuel Cells (MCFC) & Solid Oxide Fuel Cells (SOFC) are the different kinds of fuel cells (Srinivasan et. al 1999: 293 - 303).

There are several types of energy sources for the fuel cells as well as several different kinds of fuel cells[12]. Hydrogen, Methanol and gasoline are all possible sources of energy for the fuel cell car, along with other less explored options. A trade-off between sustainability and the cost of putting the energy source to use is considered the case between the options, but considerations about safety and efficiency of the fuel are also aspects of the choice. Gasoline has the obvious advantage of already having an infrastructure, but from a pure sustainability viewpoint it gives least reduction in CO_2 abatement. Hydrogen provides the most effective use of energy and would improve CO_2 abatement greatly. The downside is lack of infrastructure and problems related to Hydrogen storage. Methanol has the advantage of being able to exploit the infrastructure provided by the existing gas stations, some relatively minor treatment against corrosion and it would be possible to refill Methanol at gas stations. Although Methanol is less effective than Hydrogen it is still a large improvement compared to gasoline. The literature is diverging on the issues between fuel choices and advantages and disadvantages. On the dimensions of safety, economics, emissions and efficiency for Hydrogen and Methanol, only emissions was found to differ significantly[13] (Adamson & Pearson 2000). Other answers to those issues are usual and Rajashekara (2000) discusses different advantages and disadvantages between the different options. There is no room for elaboration in this paper, but the controversies are interesting[14], but not of any major impact in this dissertation.

Fuel cell cars have the potential to fulfil the California legislation and match the regular qualities of a car concerning speed and mileage, and are generally considered the possible car for the future. The fuel cell car is sometimes referred to as a hybrid since it has both an electric engine and fuel cells. It can be seen as an improved electric car, or as evolved from the regular EV into a new configuration. For simplicity, I will refer to it simply as a fuel cell car/vehicle or FCV. So even if the EV only is a transitory solution as Buen (et al. 1999) claimed, the EV has been important for the evolution of the FCV.

Internal Combustion Vehicle

[12] The fuel cell configurations are related to the choice of fuel for the fuel cells, but there is no room to discuss these relations in this paper.
[13] Compared by literature review.

When considering the formerly mentioned car alternatives to the ICV, it might have seemed that the development of the ICV had come to a halt, which is not the case. There is a large amount of R&D in the automobile industry, and by far the majority of the spending concerns the ICV. One must also remember a possible sailing-ship effect on the ICV; some of the efforts made for the more "sustainable cars" provide incentives and innovative efforts in fear of losing market shares.

Several factors can improve the environmental sustainability of the ICV. There is no room for exploring all of them but some examples will be mentioned. Ford does research on Hydrogen powered ICVs and Direct-injection engine and Automated-shift transmission, which can improve the fuel economy significantly (Ford Motor Company 2000). Other areas of improvement are probably also addressed, making the ICV better suited for new regulations.

Another caveat

One important caveat must be mentioned before I review the different technological options. The ongoing research on the development of more sustainable cars can be viewed with optimism for the future, but the danger is that, pressing it far, it is just a public relations gimmick.

It is one thing for the car companies to brag about their research projects. They show another face in the hearings connected to the California Clean Air Legislation. In 2003 10 % of the cars are supposed to be ultra low emission vehicles[15], where the industry (in general) is saying that it is not possible and wants a delay. Car companies put much money into research on more sustainable cars, but there is a possibility that the main reasons for doing it is connected to being scared of being left behind if a new technology is starting to dominate. In development of new technology, the presence of small companies/actors with a genuine interest in development and commercialisation of a technology is seen as important (Schot et al. 1994: 1068). Among others, BPS and IFC (International Fuel Cells) are two such companies with a strong interest in fuel cell commercialisation (Kalhammer 1998: III.3 B). Some companies or actors have the possibility of moving the limits and predictions of the

[14] SCOT could be used to study the different fuel configurations and scientific debates around the choice of fuels, as FCVs can be approaching market introduction.

[15] The discussion about keeping the demand of 10% ZEVs has been going on in May/June 2000, and the outcome will be made public by the end of this year (Fleets & Fuels 2000).

limits to a new technology, and them being the main actors in which all the other actors have to consider. Small companies with other agendas than auto manufacturers can play vital roles even though one cannot expect FCV production without the presence of car companies.

Focus of the paper

Among alternative cars, I will focus on the fuel cell driven car. This is because EVs do not seem to provide even close to ICVs regular capabilities, and additionally needs the building of an infrastructure. A FCV with some small changes might have access to an existing infrastructure and can deliver close to usual car abilities. Buen (et al. 1999) identified the FCV as better suited for the future than EVs. The hybrid is also an interesting alternative but faces cost expenses while failing to provide the same CO_2 abatement as the fuel cell car.

However the main reason for not discussing it too much is the restricted space in this dissertation. An improved ICV might be a more realistic alternative, because it is not likely that the ICV will disappear in the first decades. The big question for an improved ICV is how much it can be improved, compared with a FCV. The cost difference will be a central measure along with sustainability, if an improved ICV can provide CO_2 reductions close to the fuel cell cars. While FCVs driving on Hydrogen can imply no CO_2 release at all, ICVs would still be expected to emit CO_2. Nevertheless, Methanol is the most likely contestant for the immediate future and all the major car companies are investigating it[16] (Kalhammer 1998: III.3 B).

For the reasons mentioned in the last paragraph I choose to focus on the fuel cell car in my dissertation.

[16] DaimlerChrysler changed its focus from Hydrogen to Methanol, but still explores the use of Hydrogen especially for bus fleets.

Is the fuel cell engine a system or component replacement?

An important distinction to make when talking about a possible fuel cell succession over ICV is whether the change is a component replacement or a system change. That implies that the question of compatibility between technologies becomes an important issue.

Is the fuel cell really changing the ICV paradigm, or is it being incorporated into it? If one considers the prototypes of the fuel cell cars we see that DaimlerChryslers NeCar 4 looks exactly the same (outside view) as the Mercedes A160 class, and Fords P2000 look like a regular car. Larbaoui (2000: 9-11) stated that EVs were received better when produced by big companies than the small companies, and later linking it to psychological uncertainty. In the same way FCV producers consider using "regular" car design, to make the vehicle look like an ICV, so that the psychological uncertainty connected with radical innovations disappear.

The need for a systemic perspective can be seen through the alliance between oil companies and automobile manufacturers. Previously oil and car companies collaborated mostly on joint specific projects, but concerning fuel cell technology the relations have changed into a more overall character (Steinemann 1999:36). This change of nature indicates that the FCE (Fuel cell engine) is best regarded as a system change, and not a component replacement. Automobile manufacturers have taken a systematic perspective after starting out with an initial focus on fuel cells by itself. The focus has changed to fuels, fuel reformer technology, control technology and integration processes (ibid: 37), which must be considered a systems perspective.

As a preliminary comment it might seem that a FCV succession would involve much change and have to be considered as a system change. On the other hand, Windrum (1999) defines the FCE as a component change, which might be relatively easily changed. Windrum uses the CD player as an analogy to understand FCV introduction, but has failed to notice the important role of the automobile industry as system integrators. The complexity involved with developing FCVs is emphasised by both Kalhammer (1998) and Steinemann (1999). They indicate that the fuel cell must be considered a system change. Kalhammer and Steinemann seem to have a good technological understanding of automotive fuel cell development, while

Windrum seems to test a theory and uses FCVs as an example without understanding the complexity of it[17]. Hence, FCV development is best considered a system change.

What are the necessary conditions for technological substitution?

The literature on escaping a lock-in failure has had a fairly limited investigation compared to the focus on the lock-in on technologies, Betamax and VHS being prime examples. Contributions have been made, and now some of them will be reviewed. Then they will be discussed according to each other. An integrated set of necessary and enabling conditions for escaping the lock-in failure will be presented at the end of this chapter.

The increasing returns to adaptation argument

The increasing returns to adoption (Arthur 1988) have become a starting point for discussing competing technologies. Although Arthur's model treated technologies, which started development at approximately the same time, and not an embedded technology, some of those perspectives are fruitful. Arthur's main idea is that of increasing returns to adoption, that is, as more people or units start using the technology, it enhances its appeal. Increasing returns to adaptation have the following supporting arguments (ibid).

- *Learning by using* (Rosenberg 1982 in Arthur 1988). The notion that the more a technology is used, the more knowledge will diffuse, hence the possibility of improving the technology increases which raises the value of adoption.
- *Network externalities* (Katz and Shapiro 1985 in Arthur 1988). If the technology is complementary to other technologies and products its perceived value may rise.
- *Scale economics in production*. Usually technology can be produced cheaper if it is produced in large quantities, mass production was one of the main reasons why ICVs became a dominating technology.
- *Informational increasing returns*. The more people know about a technology tends to increase their propensity to use it. Risk averse people are rarely first users of new

[17] Which is reflected in his bibliography, but one should remember that the article referred to is only a working paper.

technology, but may be easier enrolled when information about the new technology is spread throughout society.

- *Technological interrelatedness*. As a technology becomes embedded in society other subcategories of the technology might link up to their infrastructure. The expansion of a technology might bring hardship for competing technologies.

This model is good at explaining the advantages of the first available technology, because it will gain cumulating advantages. Nevertheless, the theory has serious limitations in explaining how later arriving technologies can compete against the first mover.

If a lock-in is in place, it is hard for new technologies to enter. According to Arthur (1988) a superior technology is needed, and how can one tell from STS-perspective that a technology is superior? The other requirement for escaping a lock-in is that people know each other's preferences. All actors are presumed to know about the "superior" technology, furthermore know that everybody wants to make a technological shift. If the information is not available people generally do not want to be the first to make a change, because of the advantages connected to existing technology, and the fear of the high cost of being the solitary actor who changes technology (Farrell and Saloner 1985 in Arthur 1988).

The general impression when it comes to escaping a lock-in failure is that it is extremely hard and can only be done under harsh conditions. But the Arthur model has some flaws, and one of them is that Arthur's lock-in result only applies when you have linear returns and relatively homogenous consumer preferences (Bassinini & Dosi 1998 in Windrum 1999: 12). The demand for cars cannot be homogenous, if one uses the variety of cars as a representation of consumers' different preferences. The choice of different cars today with differences in design, safety, and driving abilities and other luxury options implies vastly differing consumer preferences.

Another flaw in Arthur's model is that one cannot expect utility to be proportionally increasing along with the size of the user base (Swann 1998 in Windrum 1999), which implies that the increasing returns to adaptation are less than expected in Arthur's model. The ICV is a good example of Swann's argument. As the numbers of ICVs on the road increase, so do constraints on infrastructure and environment. Those constraints could be said to decrease overall utility, especially in urban areas with low air-quality and rush hour problems.

The problem-solving capacity of the technology also plays an important part in the supporting arguments for increasing returns to adaptation. But Frenken & Verbart (1998 in Windrum 1999) show that the problem-solving capacity of the technology affects the returns, but it does not necessarily increase with user base. Problems like CO_2 pollution are not necessarily progressing just because more people are driving cars.

Possible advantages for new technology

Another study more directly related to the escape of lock-in and a sustainable car is Cowan & Hulten's (1996) article about how electric vehicles can escape the ICV lock-in. Like David (1985 in Cowan & Hulten 1996), the authors emphasise that new competing technologies must be more than competitive. David claims that 20 to 30% improvements are not necessarily enough to make users change technology (QWERTY & Dvorak example). Additional advantages must be added if a new technology is to succeed. The following factors may provide beneficial for new technologies (Cowan & Hulten 1996):

- *Crisis in the existing technology*. Some kind of failure needs to be connected to the embedded technology.
- *Regulation.* Government requiring changes might provide opportunities for emerging technologies.
- *Technological breakthrough producing a (real or imagined) cost breakthrough.* Lower prices or expected lower price gives a technology advantage in facing competitors.
- *Changes in taste.* Trends and market demands might give emerging technologies an advantage.
- *Niche markets*. A protected market with consumers willing to take the cost in the start-up face of a technology provides companies with learning and adaptation and possibly some economics of scale.
- *Scientific results*. Scientific results may emphasis the need for better environmentally sustainable technologies, and scientific support may prove useful for a specific technology.

Some of the points mentioned are a bit general, and all of them concern society. Mainstream strategy would have problems dealing with these issues. But AoD and strategy will be used to discuss these issues later. An interesting question is how strategic alliances can influence these factors.

Technology adaptation and compatibility

Other interesting aspects on escaping a lock-in are mentioned by Windrum (1999), who uses the increasing returns to the adoption model as a starting point along with the literature on path dependency and lock-in. But Windrum changes the focus as he additionally uses Shy's (1996 in Windrum 1999: 4) framework, which name three dimensions that affect technology adaptation:

- Technology growth and number of users.
- To what extent a new technology is compatible with the old one.
- How users perceive the trade-off between the already existing network and its advantages compared with the advantages of the new technology.

The third point probably depends on the degree of complementarities and compatibility discussed in point 2. If compatibility is high some negative effects of switching to a new technology disappear and the trade-off changes in favour of the new technology.

Compatibility is insufficiently considered in the lock-in literature but is likely to be of importance (Windrum 1999: 13). FCVs are unlikely to be an exception to the importance of compatibility in escaping a lock-in failure. The car and its surroundings can be seen as techno-economic network consistent of roads, lifestyle fuelling infrastructure and other elements. When considering the car, it is important to recognise it as an emblem of modernity (Rip & Kemp 1998: 335). An alternative propulsion vehicle that goes against all aspects of TEN expects to face harder resistance if it tries to establish itself. It would have to compete against the common perception of a car, as previously shown.

Windrum (1999) concludes with three necessary conditions for a new technology to be able to exceed an embedded technology:

- Limited returns to adoption. If the embedded technology never loses its increased value with adaptation - than there is no room for an emerging technology without those advantages.
- A radical and related new product or process technology. The technology needs to be radical to perform good enough to compete against an established technology, while related technology has the potential of making the adaptation process easier.
- A new way of controlling the new process or product and the interaction, in a way that is underneath the supporting context, as with a scientific paradigm.

Windrum's second and third conditions seem interesting. Condition number two states that emerging technologies need to be both radical and related. It can seem like a strange and tough request, however when it is possible it might prove influential. When the radical technology is related as a component in the system, one can easier achieve radical change because the overall concept has not changed. Additionally the technology can diffuse easier within a system than a new system could, because risk and psychological uncertainties can be reduced when the technology is perceived as related. Can one expect to find a technology that is both radical and related? Intuitively they might seem as counterparts, but that is not the case. Kemp (1994) shows that most radical technologies are not completely new but are related to familiar technology. FCVs can be seen as evolved from EVs as both run on electric engines.

The third condition is fairly extensive and demanding, but in this context I find it useful because it highlights the multidimensionality of technological progression and focuses on several actors and institutions involved in the change. Windrum (1999) operates with three dimensions: business environment, regulation/state environment and social environment, which can be considered to constitute the TEN. Some kind of control of the TEN, is in many ways similar to control of the technological nexus pointed out as the strategy for technology succession by Schot (et al.1994).

Integration of conditions for escaping a lock-in

Views on necessary conditions for escaping a lock-in have been discussed, but what is the final impression and which conditions need to be fulfilled if a new technology is to succeed?

A strategy for technology succession should have an evaluation of the strength of the established technology in accordance to the increasing returns to adaptation model. The supporting arguments of Arthur's model also give some hints of necessary conditions: a new technology must achieve economics of scale to be able to compete and replace an established technology. The supporting argument of "*Informational increasing returns*" can also work as advice the other way around, even though the existing technology has the greater advantage. The new technology needs to become known and recognised as reliable if it is to succeed the older technology.

The six advantageous conditions mentioned earlier by Cowan & Hulten (1996) should be considered, some are helpful and others are crucial. A technological breakthrough providing a competitive price and high technological quality and abilities are crucial for diffusion of FCV technology. Some kind of discontent with the existing technology is also necessary, because it gives the new technology an advantage. Having an advantage based on the negative qualities of the old technology is useful, as the first generation technology is likely to have some flaws and problems. The advantage based on problems with the existing technology might make it possible for the new technology to survive and improve its first generation product or processes.

The other positive factors for technological succession might interact and prove positive for a new technology, and some of those factors are possible to influence for powerful alliances.
An important point highlighted by Shy (1996 in Windrum 1998) is consumers' perceived trade-off between the advantages of new technology and the advantages of the existing network. If the issue is within alliance reach, it is beyond the reach of this paper to explore the possibilities of marketing in changing fuel cell preferences.

Windrum's (1999) conclusion names three necessary conditions for escaping a lock-in failure. The first one is simply limited returns to adaptation while the next ones are more interesting. The new technology needs to be both radical and related, and this can be difficult as discussed earlier. A radical and related technology will have a great advantage, but it is not absolutely necessary for technological substitution. Some kind of control of the TN was identified as a strategy for technological succession and is considered important.

Necessary and enabling conditions for technological substitution

From the literature reviewed and discussed I put forward a suggestion of necessary conditions and enabling conditions for a technological succession[18].

Conditions necessary for escaping a lock-in:

- A technological progress in a new technology that makes it competitive on the dimension of abilities and quality.
- Economics of scale is necessary to compete on price and the other competitive dimensions.
- Discontent with the embedded technology on one or more points, which provides the new technology with some kind of improved function compared to the established technology.

Possible enabling conditions for escaping a lock-in:

- If the new radical emerging technology is complementary and compatible with the old technology, than the new technology can draw advantages of the already existing network.
- Limited increasing returns for the embedded technology.
- State regulation and other regulations might present advantages to new technology if the new technology is accustomed to the regulations, while the older technology might be forced to make costly changes or pay taxes.
- The availability of niche markets gives possibilities for learning and improvement in "friendlier" environments.
- New trends might favour new technology.
- Scientific results might influence regulation, policy and adaptation of new technology.
- Some kind of control over the influencing factors in the network surrounding the technology.

[18] The final set of conditions is nothing more than a suggestion, and is abstract concepts open for discussion. As the topic of escaping lock-in failures are investigated further, it is reasonable to assume that shortcomings will emerge in the framework developed in this paper. But as a set of conditions was necessary for other parts of the paper, hence I have chosen to go along with it.

In a later chapter both categories of conditions will be discussed on how the use of strategic technology alliances might fulfil these conditions. The exception is the last enabling condition as it is discussed as the strategy for achieving all of the other condition.

4. Automotive fuel cell arenas of development and the role of strategic alliances

Introduction

The main FCV arenas of development will be outlined, and their use of alliances in creation of a technological nexus will be discussed in this chapter. How strategic alliances are used to gain control or influence in the technological nexus will also be discussed. With several powerful arenas, it is hard to tell which one is likely to be first to market, and which ones will be successful. However, two arenas stick themselves out: the "Alliance" and the GM and Toyota alliance. Both alliances are powerful consisting of dominant companies connected with several partners, and new competitive developments are likely to emerge from either one. BPS, Ford and DaimlerChrysler use their alliance as a strategy for being the first mass-producing actor[19] of FCVs (Panik 1998:37). Toyota expects to be the most likely first mass producer, in spite of the beliefs of the actors at the other important arenas (Kalhammer 1998). The “Alliance” has a more proactive strategy towards FCV development than the other developers, and will be the focus for discussing how alliances can be used to build a nexus and how alliances can be used to strengthen the actor’s own position. The BPS, Ford and DaimlerChrysler alliance is generally considered to be so important that it is usually referred to just as the “Alliance” (Maruo 1998:43), which will be done in this paper as well. Partial connections have significance in the arenas of development and will be considered.

Automotive fuel cell arenas of development

The most important arenas and actors in automotive fuel cell development are presented in this paper[20]. In FCV development, the actors are many and heterogeneous, and placed at different locations, but the important roles are all within the triad countries. The actors vary

[19] As this paper was written before the inclusion of Ford, there is no discussion between DaimlerChrysler and Ford about which company is going to be first to the market with a FCV.
[20] It is not possible to present all arenas and actors in this dissertation. Emphasis is put on the automobile manufacturers, that are considered important. The variety amongst actors can be seen in appendix C, which enlists a number of the actors involved in automotive fuel cell development.

from large-scale automobile manufacturers to specialised fuel cell developers, along with research institutions, government agencies and environmental NGOs.

The fuel cell[21] is one of the main actors, along with oil companies and even oil if one would want to go further from the "centre of translation" in the network. The different fuel cell configurations as well as possible fuel solutions also play parts in defining the network. The differing fuel options is not merely a technical issue, because the fuel option influences the general design of a fuel cell engine, which is a issue of power for the different FCV developers. Gasoline as fuel would improve General Motor's (GM) strength, while DaimlerChrysler is especially strong on hydrogen, while most of the involved companies have experience with Methanol as a fuel. The technical choice between fuel solutions has social and strategic implications for the different arenas.

After Grooves discovery of the fuel cell in 1839 (Srinivasan et al. 1999: 283), Allis Chalmers reopened the arena with the fuel cell tractor in 1959. Eight years later, GM had a prototype fuel cell van ready. Nevertheless, both prototypes performed below expectancy and those arenas of development were (temporarily) closed down (Steinemann 1999). Technical problems and cost interrelated, such as the high level of platinum required; made the companies abandon the vehicles.

In the following decades, two major breakthroughs took place. At LANL (Los Alamos National Laboratory) some actors achieved an OPP when the amount of platinum needed decreased from the cost of 50 000 US$ to some hundred $ pr. car (ibid). The cost reduction was an OPP because the amount of platinum previously required was by itself enough to hinder successful automotive FCV commercialisation.

At Ballard Power Systems Inc.[22] in Canada 1987, another important milestone was reached. The power density of fuel cells came close to that of the ICEs, and 4 times higher than Dupont's previous record. Daimler-Benz[23]and GM saw this development as inspirational (ibid). Technological trajectories were pointed out as playing a part in arenas of development

[21] Of course there are many possible configurations of the fuel cell, so referring to the fuel cell is difficult since there are still many aspects of a fuel cell engine open for negotiation.
[22] In 1987, it was named "Ballard" only.
[23] Daimler-Benz merged with Chrysler in 1998 and took the name DaimlerChrysler at that time.

(Jørgensen & Sørensen 1999), and it seems to be relevant in the case of automotive fuel cells as well. Only the car companies with previous involvement with FCV development realised the consequences of the previously mentioned performances (Steinemann 1999: 28). The companies that did not have the right knowledge intermediaries were unable to translate or comprehend the developments, and lagged behind.

In the 60s and 70s, Daimler-Benz explored different fuel options, especially Hydrogen, and Daimler-Benz also experimented on electric and hybrid engines. When BPS published their 1987 breakthrough, Daimler-Benz quickly renewed their interest in fuel cells and soon established contacts with BPS (Kalhammer et al.1998). Exploration of the fuel cell for automotive use was started in 1990 and four years later, the prototype NeCar 1 was finished. NeCar 1 had BPS fuel cell stacks integrated into a Mercedes-Benz van design (ibid). NeCar 1 is pictured below (Ballard 2000):

The BPS, DaimlerChrysler and Ford arena

BPS and Daimler-Benz initiated a 4 year collaborative agreement in march 1993, and expanded the collaboration in 1997 into a 450 million dollar alliance consisting of two joint ventures: “dbb fuel cell engines”[24] and “Ballard automotive”. In December 1997, Ford was included in the alliance as well, and the joint venture “Ecostar Electric Drive Systems» was established between the three alliance members. The ownership between the three companies and their joint ventures are explained for the interested at BPS (2000) and Xcellcis (2000). Xcellcis is working on fuel cell engines, Ecostar is developing electric drive trains while Ballard Automotive is working on offering an integrated fuel cell engine (ibid). Daimler-Benz merged with Chrysler, which had a small FCV project before the merger, and provided the alliance with increased manufacturing capabilities as well as market knowledge. Because of the merger, Chrysler aborted its fuel cell development, while Mercedes-Benz terminated their EV development.

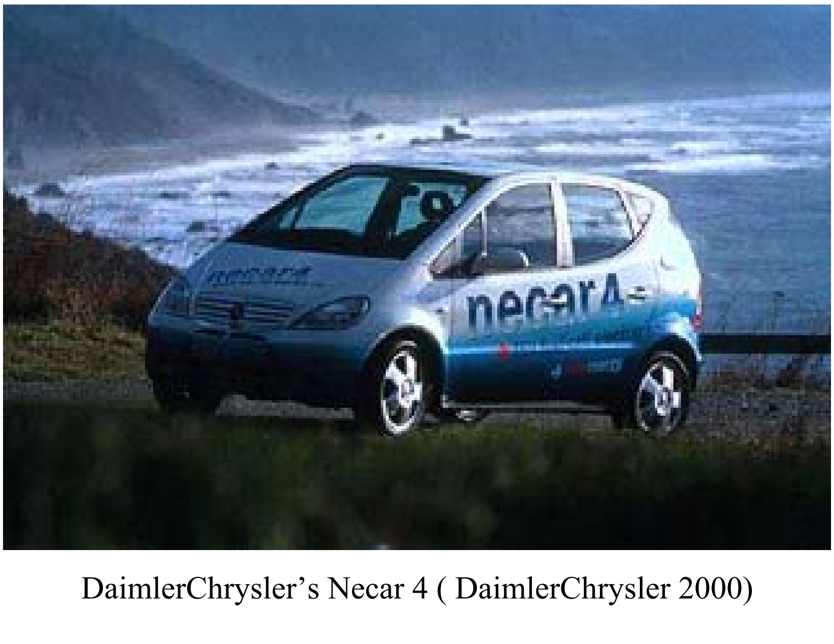
Developing fuel cells for automotive use is not a simple task, but a rather complex and expensive task. BPS operates mostly on fuel cells in itself, in stationary, portable and automobile use, but does not focus much on fuel cell vehicle integration[25]. DaimlerChrysler works on integrating the fuel cell engine into the car, and learns about the whole process through the alliance's joint ventures. Both Ford and DaimlerChrysler have large-scale car manufacturing experience. Another strategic reason based on technology for enrolling Ford into the cooperation was Ford's experience with drivetrains for electrical cars. Ford has worked several years on developing electrical cars, and has Think EVs on the roads in Scandinavia. What the companies in the "Alliance" are working on is partially complementary aspects, as each company have specific contributions. Ford and DaimlerChrysler have overlapping capabilities of course, but their core capabilities contributing to the development of the fuel cell cars are different. So being three companies with three joint ventures on specific areas combines a lot of technical knowledge, which make a basis for the technological nexus. Financial reasons can also be the main reason for enrolling Ford into the alliance (Maruo 1998). Ford lacked fuel cell competence, but had money to put into R&D. Both are important intermediaries in technology development. Maruo neglects that even though DaimlerChrysler has experience with electric engines it can not be considered as experienced as Ford on EV technology. Both money and EV experience probably played a part in the decision to enrol Ford into the alliance.

Ford and DaimlerChrysler are two of the four largest mass-producing car companies in the world. Ford was previously without specific fuel cell knowledge, but had lots of experience in producing drivetrains for electric cars. BPS and DaimlerChrysler are probably the two most experienced companies on fuel cell technology, reflected in the manpower and money spent on the technology. BPS has been working with fuel cell technology since Geoffrey Ballard was to evaluate fuel cells for the Canadian government in 1983. BPS is the main producer of fuel cells stacks, and has diffused their technology to most of the major car producers. The joint ventures are doing their specific assignments, while Ford and DaimlerChrysler are

[24] Which was renamed to "Xcellcis Fuel Cell Engines Inc" on the 17th of February 2000.
[25] But the joint venture Ballard Automotive develops and aims to offer integrated fuel cell engines to other vehicle manufacturers.

looking at system aspects of fuel cells and working on the integration of the FCE into their own cars. Ford and Daimler Chrysler's top of the line fuel cell vehicles is shown at the next page:

The P2000 Prodigy Hydrogen Fuel Cell Vehicle (Fuel Cells 2000)



DaimlerChrysler's Necar 4 (DaimlerChrysler 2000)

"Alliance" Strategy

Ballard's strategy in relation to alliances is to connect with the top global players in the areas they are involved (Ballard 1999), which can be seen as a strategy to stay involved with the most influential actors in the network. Is cooperation control? Yes, it is a form of partial control, but of course not total control. Through their alliances, BPS has better chances of influencing their partners choices, than they have to influence the choices of Toyota. Cooperation or enrolment seems to be an expressed strategy at DaimlerChrysler, Dr. Panik[26]states that cooperation is the way to go to accomplish and pass hinders in relation to infrastructure and technical problems as well as cost issues. Furthermore, Panik claims that DaimlerChrysler is willing to bring its already acquired knowledge into any new co-operative agreements (DaimlerChrysler 1999). DaimlerChrysler is willing to support the development of technology through openness and cooperation, and not secrecy and licensing strategies. This strategy of inclusion[27] can diffuse the "Alliance" technology into other arenas of development. Panik also expresses that cooperation with governments is necessary for fuel cell market introduction, to open markets and other infrastructure-related issues as training of the job force (ibid). Not only is government support essential for those tasks, but government support of a technology is generally known to give both the technology and its developer's greater credibility (Tidd et al. 1998:224). If a government is enrolled, it can evolve further and improve that country's engineering capability through school and university institutions.

Lacking information from Ford, the other players in the "Alliance" seem to have co-operative alliances on the agenda. I assume that Ford shares the same enthusiasm and that it can be considered a joint strategy for the "Alliance". In this paper, the "Alliance" is treated as one actor, even though internal differences may differ within the alliance. The "Alliance" is considered as one actor, because their outward statements seem to agree[28]. All the members or actors in the network participate in other alliances as well. As an example, BPS has strategic alliances with other companies on fuel cell development for stationary and portable

[26] He was formerly fuel cell project director at DaimlerChrysler, and now CEO at Xcellsis.
[27] Inclusion is one of six strategies for technological development identified by Jørgensen & Sørensen (1999)
[28] Most strategies can be identified from outside the company, but some elements of a strategy can only be seen from inside the company (Thompson & Strickland 1996: 10). I assume that the strategy seen from outside is similar to the strategy inside the companies in this case.

fuel cell products[29]. In the later discussion about the "Alliance" and its connections, I will refer to a connection between any member of the "Alliance" and others as a connection between the "Alliance" and others. Knowledge diffusion throughout the "Alliance" is assumed, which is not so problematic in a pre-competitive phase of FCV development.

There is the question whether or not one could say that the "Alliance" is aiming at becoming the "centre of translation" in the development arena. In relation to digital hearing aid some Danish manufacturers operated with the strategy of becoming the centre of translation and wanted to use software technology as the OPP (Sørensen 1999: 10). In trying to achieve those aims the Danes built up a complex network with actors such as computers, strategies, perspectives, companies and other heterogeneous actors (ibid: 11). Can the "Alliance" be considered doing this in FCV development? The emphasis on collaboration and knowledge diffusion, and the positive view on enrolling new actors seem to support the view that the "Alliance" has a strategy of becoming the centre of translation trough inclusion and co-operative efforts.

The GM and Toyota arena

General Motors or GM, was involved with fuel cells in the sixties, and became active in 1990 in cooperation with LANL, US Department of Energy (DOE), Amoco and some adversaries of GM. Today GM are cooperating with Dow Chemicals, Dupont, Amoco, ARCO, Allison and ExxonMobil (Steinemann 1999: 39). Toyota's fuel cell involvement has been mostly in-house, but they are cooperating with Panasonic JV, ExxonMobil and their own adversaries: Aisin Seiko and Denso (ibid: 38). Both GM and Toyota and Toyota lanced a five-year plan on cooperation on alternative propulsion technologies, including fuel cell technology (ibid:21). However, others have reported that the agreement does not include fuel cell technology (Maruo 1998:45). Both companies are connected to ExxonMobil and are likely to have some kind of cooperation, although it is unsure if Toyota and GM are cooperating on fuel cell vehicles specifically.

[29]Portable and stationary fuel cells applications are probably closer to commercialisation than automotive products, but there is not enough space in this paper to investigate those issues thoroughly. All the hype is on the automobile application, which is reflected in what is written about fuel cell development, as well as in this paper.

GM and Toyota are cooperating with other companies by themselves on fuel cells, which enables them to expand their knowledge base (Steinemann 1999:20-21, 39). Both companies take the development seriously, but Toyota expects to be the most likely first entrant catering for a mass market (Kalhammer 1998). Even though it may seem that Toyota is lagging behind the technological leaders, they have previously proved an ability in being quick to market once the development stage is finished. The pictures are of GM's (trough Opel) Zafira and Toyota's RAV 4, both companies newest fuel cell vehicles:

(Fuel cells 2000)

The French arena

The French projects have been working on several technical dimensions of the new technology, and the joint PSA-Peugeot, Citroen and Renault programme have been supported through Joule, Thermie, FEVER and HYDRO-GEN projects. Other actors enrolled into the French arena are De Nora, Air Liquide, CEA, ELF, Total, Valeo and the French Ministry of Education, Research and Technology (PSA Peugeot Citroen 1999). The technical development seems to be lagging behind. The joint projects planned to present a fuel cell car in June 2000 running on a 30 kW fuel cell while NeCar 4 was running on a 70 kW fuel cell in 1999 (PSA Peugeot Citroen 1999 & Xcellcis 2000). Maruo (1998:45) also considers FEVER to be lagging far behind the BPS-Ford-DC alliance. With such a technological lag, one cannot expect the French manufacturers to play a leading role in automotive fuel cell development.

Other arenas of development

As alliances almost have become the norm within fuel cell development, there are other important arenas involved in FCV development, described by Avadikyan (et al. 2000: 39-40). The previously resistant BMW has started cooperation with International Fuel Cells, which can be considered an experienced fuel cell manufacturer. Nissan and Renault have established a joint venture, which have the potential of increasing their fuel cell competence. It is interesting to note that alliances are being used in a large scale in FCV development, and not only among the most influential actors.

How have alliances contributed in creating a technological nexus?

A network or arena gains resistance as several heterogeneous actors support it, as suggested by Callon earlier in this paper. Therefore, enrolments of heterogeneous actors will over time strengthen the arena and make it more resistant to challenges. The oil companies contain technological heterogeneity and knowledge capable to support a technology and its nexus, and are able to make the TN more resistant to challenges. Increasing numbers of auto manufacturers who support the FCV technology, can be expected to increase the nexus resistance against challenges. The extensive use of alliances play a significant part in the creation and strengthening of a technological nexus. The speedy enrolment of new actors, specifically research institutions and specialist companies, which are making joint efforts to solve technical uncertainties and interrelated cost problems, is beneficial for the nexus. The contributions of a variety of core capabilities, can increase the problem-solving capacity of the TN. Enrolment of energy companies and other actors' trough alliances contribute in strengthening the nexus, as alliances have become usual in fuel cell development.

How has the "Alliance" contributed in the creation of a technological nexus?

The "Alliance" has been vital for the creation of a technological nexus, as the pioneers in automotive fuel cell development can be said to have partially reopened the arenas. The

"Alliance's" further developments and results have been important for enrolment of new actors, and it still is. Daimler-Benz and Ballard started their cooperation in 1993, and NeCar 1 arrived a year later. Daimler-Benz pronounced interest in fuel cell signalled by NeCar 1, preceded a flow of new arenas of development (Steinemann 1999: 19), and shows the strategic importance of market signals[30] from recognised actors. The example shows the importance of the symbolic implications of the choices taken by important actors, and show that other companies are influenced by their choices. The significance of actors like DaimlerChrysler is large, because their actions are symbols and guidance for other companies, which reinforces DaimlerChrysler's choices into the rest of the industry (Schaffer & Uyterlinde 1998:258). Significant actors have the possibility of influence and partial control over the technological nexus. Their technological performance combined with high social prestige and recognition in the FCV arenas, are a source of influence and control. Perceived technological strengths lead to higher social prestige, which can enable actors to partially control technological development. Perceived technological strength is probably linked to the value of a company's brand- name(s). A well known brand name can work as a customer guarantee to a larger extent than the actual warranty of the product, and can support the customers' belief in a new radical product (Hamel & Prahalad 1996: 276-280). The billions of dollars already invested in companies like Ford, GM, Toyota and DaimlerChrysler is likely to give them particular strength when the product is as radical as a FCV will be. BPS must be considered a recognised brand name within the car industry, and specifically within the FCV industry. The technology cooperation between BPS and DaimlerChrysler signalled the cooperation of two of the most competent actors in the FCV arena. The cooperation makes other perceive them as technical strong, hence giving them social power by relating to them as the number one developers of fuel cell technology. The expanded cooperation with Ford, which is the second biggest car manufacturer in the world, increases the strength of the alliance. As some of the most renowned brand-names world-wide are involved with fuel cell technology, consumers can be expected to be more willing to consider radical technology because of reduced psychological fear.

The "Alliance's" consistence and technological progress has made enrolment of awaiting companies easier. The "Alliance" has gathered a network that covers all the dimensions of FCVs (Steinemann 1999:38/39). Along the technical and scientific dimensions, a number of

[30] Market signals can be defined as direct or indirect strategic communication, as a means to influence the

specialist companies are involved in fuel cell development in cooperation with the “Alliance”. Methanex Corporation is the biggest Methanol producer and cooperates with BPS on Methanol for FCVs (Maruo 1998:20). Catalyst company Johnson-Mattey is also cooperating with BPS in fuel cell development. The “Alliance” is in general involved and cooperates trough alliances with specialist companies in the scientific and technical disciplines required for fuel cell development.

The diffusion of BPS fuel cell technology as seen by licensing of technology to WV, Volvo, Honda, Mazda, Nissan, Honda, GM and Delphi can be seen as enrolment of actors into the technological nexus. The "Alliance" is the centre of translation as their licensed technology works as an obligatory passage point. For many of the licensees, the licensed technology have been starting points for further work on FCV development, which is another reason why the Ballard alliance can be seen as a lead actor in development of fuel cells. Licensing away technology provides other companies with knowledge about the new technology, and makes it easier for companies to get involved with FCV, thus contributes to the making and strengthening of a TN.

MobilExxon and Shell are connected to the alliance as well, which give the alliance more expertise and power on the fuel side, which is an important aspect of the technology. Ford cooperates with Exxon, and DaimlerChrysler cooperates with Shell. Enrolment of oil companies into the nexus is vital as it co-opts competition at the same time as it enrols new resourceful actors into the nexus. The enrolment of oil companies can also contribute in negative ways, if the oil companies have their own strategies and try to become a centre of translation themselves. Mitsubishi oil is the link between parts of the Mitsubishi Corporation and DaimlerChrysler, which extends the network even more. As DaimlerChrysler is to buy 34%[31] of Mitsubishi, DaimlerChrysler is in a position to influence strategic decisions concerning the company’s alternative propulsion technology. DaimlerChrysler's expected share in Mitsubishi could be considered what Maruo called strategic shareholding. It can give DaimlerChrysler a certain amount of influence on Mitsubishi’s actions, and increases the likelihood of enrolling Mitsubishi into the arena.

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environment. It can be realistic statements, or bluffs designed to deceive competition (Porter 1980: 75-76).

[31] As Mitsubishi recently is scandalised, there are rumours of DaimlerChrysler buying a larger percentage to a lower price.

How have GM and Toyota contributed in the creation of a technological nexus?

Both companies are working on the technology, but to a lesser degree than the "Alliance". Their developments and workings seem to ignore the social dimension of fuel cell technology, and partially ignore the network of the car. Both companies are regarded as ready for FCVs market introduction from 2004 – 2005, but are more reserved in their view on development than the "Alliance" (Steinemann 1999). As Toyota has been working on FCVs predominantly in-house, it can not be considered to have contributed much to the creation of a technological nexus. When Toyota collaborates with ExxonMobil and GM, their actions are noticed. The mere presence of Toyota and GM is likely to have an effect. Lack of involvement from GM and Toyota could be considered market signals about the lack of belief in fuel cell technology. Such a message from GM and Toyota could potentially undermine other actor's beliefs in fuel cell technology. The overall acceptance of fuel cell technology among all the major auto manufacturers sends important signals to the surrounding environment, especially about the knowledge required for future car production. Relatively homogenous positive signals about FCV technology, makes involvement in the technology to be perceived as less risky, which is positive for FCV development. The strategic importance of involving the automotive supply chain in fuel cell development is large. The OEMs who manages to enrol them into their development can increase their chance of a successful commercialisation of the technology. Steinemann (1999:45) comments on the lack of suppliers involved in fuel cell development, and expect these, especially the first-tier suppliers, to play important roles in an eventual market. New actors are thus expected to emerge, but the first-tiers are expected to emerge at already existing arenas and not independent arenas.

Other arenas

Although the French arena can not be expected to have the same influence as the technological leaders, the developments still have significance. The arena in France is important because more European companies are involved with fuel cell development. The joint focus of FCVs across continents play a part in governmental and company policies, and strengthen the nexus. Nissan's cooperation with Renault and BMW's cooperation with International Fuel Cells are examples of how alliances are used to join capabilities in the quest for technological development. For many actors alliances can be considered a necessary approach to enable technical and cost requirements of the emerging technology. As the number of arenas is growing along with new specialised actors, and the auto manufacturers are building knowledge and capabilities to integrate a FCV the problem-solving capacity of the FCV nexus may increase.

Partial connections between the arenas of development

The "Alliance" and the Toyota-GM alliance are strong, but it is not likely that the overall build up of knowledge will come only from a handful of companies, but rather involve a larger part of the value chain (Gagnon 1999:97). Partial connections between the different arenas of development can be important in the creation of a technological nexus. Partial connections can facilitate diffusion of knowledge among the three dimensions of the technology, and provide synergies between developments at different arenas. The advantages of competing projects can be increased with partial connections that can drive the technological progress faster. Some actors have the role of being partial connections, and some of them are important. CARB, California Fuel Cell Project and USCAR will be sketched.

California Air Resource Board (CARB) is an important actor. If the “Alliance” had not been so powerful, CARB might have been considered the centre of translation. Through intermediaries (laws), CARB managed to put ZEVs, ULEVs, LEVs, TLEVs and emission reduction in general on the agenda for several different actors (Schot et al.1994: 1064). In the network surrounding CARB, some important actors and lack of actors are partly responsible for CARB’s actions. Nature played a part, as southern California is one of the most polluted areas in the world. The lack of an influential car producer in California has made making environmental claims easier, because there was and is no local auto industry to upset (ibid). The legal proceedings are not ready yet, but it is apparent that CARB has provided strong incentives and encouraged different arenas to get involved in development of environmentally sustainable cars. Grass root pressure extended the CARB regulations to twelve other states, thereby increasing its power through mobilisation of other actors.

Through the “California Fuel Cell Partnership” new actors have been enrolled into the TN. These include the State of California, Shell, Arco, Texaco as well as Ballard, DaimlerChrysler, Ford and their joint ventures. As new actors are taken front stage, new possibilities emerge. Enrolment of California and the energy companies gives fuel cell technology more power. It is probably easier to introduce fuel cell cars with the help of the large energy companies, rather than compete against them. Co-option is one of the main reasons for entering an alliance, as previously mentioned (Doz & Hamel 1998). The oil companies can resist the FCV network, but when those companies are enrolled, they pursue the same goals, instead of conflicting goals. The use of alliances with creation of the "California Fuel Cell Project", which is supposed to test 50 FCVs between 2000-2003, is a way of making other actors test and use their technology, and could be said to be a mobilisation of new actors into the network. The enrolment of the state of California and petroleum companies has strategic impacts for FCV commercialisation. When all dimensions of the technology are covered, it is easier for the companies to prepare and launch a commercial breakthrough.

It is interesting to note that GM have a relationship to Ford and DaimlerChrysler, which all participate in USCAR (United States Council For Automotive Research). The US car companies collaborate on joint technological and environmental concerns. The organisation co-ordinates research programmes with US government, as well as joint consideration of new technologies and some degree of result sharing on research projects[32]. This goes to show the partial connections between the different arenas of development. The connections between US companies and interests play important roles in fuel cell development. USA has a large automobile market, and its manufacturers can be expected to play an important part.

Project competition combined with partial connections has probably been good for development of fuel cell technology. The big three in USA (GM, Ford and DaimlerChrysler) were never able to reach an agreement during their discussion of building EVs together (Gagnon 1999: 96). A state of no agreement may have increased competition and hence the need for each company to stay involved with development at (approximately) the same level as their competitors. Cost reduction is a reason for joint technological development, which indicates that competing projects probably increased the overall investment in fuel cell technology.

[32] The web page is rather vague, and I have no additional information about how specific on technical solutions this sharing is. As an indicator one might have to consider the share of "common" and "private" benefits to the specific partners in specific projects (Khanna et.al 1998), but one should always remember that these companies are fierce competitors on the market.

The partial connections have played an important part in strengthening the nexus by facilitating coordination, co-option and diffusion of knowledge in the technological nexus.

How have alliances been used to gain influence and control within the technological nexus?

Strategic behaviour from the "Alliance"

The "Alliance's" participation in agreements can be seen from a strategic point of view. The "Alliance" being the largest and dominating actor is likely to have more power and receive more influence in collaborative projects. That process can be reinforced if their technology and knowledge is "given" away (through participative projects), which allows other actors to hook up to their technology. In this way, the "Alliance's" technology can become the OPP and gain cumulative network advantages.

The extensive use of alliances by the "Alliance" can be considered a strategic tool. DaimlerChrysler, BP, BASF, Methanex Corporation, Statoil and Xcellcis have signed a joint agreement. The agreement is based upon joint evaluation of necessary actions and conditions before a Methanol FCV configuration can be implemented (Methanex 2000). Methanex, BP and Statoil all are experienced Methanol producers. The "Alliance" is taking part in technological cooperation among some of the world leading actors concerning Methanol. The goal of the agreement is to openly publish the results, and eventually implement the necessary conditions (ibid). The discussed and publishing of the results to come, emphasises the "Alliance's" strategy of influencing the technological nexus trough sharing knowledge and enrolment of other actors. An intergovernmental alliance works in two ways. First, it supports the build up of a strong technological nexus. Secondly, it can reinforce the "Alliance's" position as the leading arena. The "Alliance" is the only FCV developer involved in the agreement, therefore the FCV configuration can be considered the OPP, and the "Alliance" the centre of translation. As more companies, governments, artefacts and other intermediaries are connected to the "Alliance" FCV configuration, their configuration gains more support and power and reinforces the "Alliance's" strength.

GM and Toyota

Toyota and GM signed a collaborative agreement the day before California Fuel Cell Partnership, which included the "Alliance" plus the oil companies Shell, Arco and Texaco as well as CARB and California Energy Commission signed an agreement (Brooke 1999). The Toyota-GM alliance can be interpreted as a reply to the "Alliance", in fear of being left beyond control of the technology and issues surrounding it. A co-operative agreement between GM and Toyota obviously receives attention, and has the strength to influence technological development and challenge the fuel cell solutions made in the "Alliance". It seems like GM and Toyota realized the power of the “Alliance”, and opted for the same strategy in an attempt to gain some influence to counter the power of the “Alliance”.

The other arenas

It is hard to tell how the alliances are used to gain power in the network, because the other arenas are so much smaller with less influence than the two powerful arenas. A simplistic notion could indicate learning and imitation strategies, or trying to achieve a good position before eventual market competition. Imitation strategies can be powerful, because not all companies can be first to market. Staying involved with FCV technology can enable companies to improve their capabilities over time, and be ready for a mass market.

Concluding remarks

The ”Alliance’s” technical and social performance and prestige are sources of power and influence in the FCV arenas of development. The perceived power and influence makes the “Alliance’s” choices to be seen as important market signals attended to by the other actors. Important actors are positive for the development of a technological nexus, because the “Alliance” has the power to push the technological development further, by its investments. The “Alliance” choices can be regarded as market signals, which the other companies pay respect to. As auto manufacturers follows the “Alliance’s” market signals to avoid the risk of lagging behind, its power and influence is reinforced. The use of alliances and specifically the “Alliance’s” use of alliances have been vital for the creation and mobilisation of a technological nexus. A number of different arenas and alliances have contributed in creating a nexus, which in some extent has reinforced the "Alliance's" control and influence in the nexus.

By contributing to a build up of a technological nexus, the "Alliance" also reinforces its own power position. By being the centre of translations in a number of alliances, the "Alliance" manages to get "authorship" over the alliances. Enrolling several actors into the nexus, and the "Alliance" FCV configuration, diffuses the "Alliance" technology and reinforces its strength trough increasing returns to adaptation.

Partial connections have been important for the development of a FCV technological nexus. The partial connections facilitate knowledge diffusion trough the different arenas, and allow easier integration of discipline specific knowledge. Forums that go across arenas have the potential of ensuring a higher degree of compatibility between the different arenas of development. The important role played by CARB should be emphasised, because it created incentives throughout the industry, and connected different arenas of development.

5. How can a technological nexus fulfil the necessary and enabling conditions for escaping a lock-in?

Till now we have seen how strategic alliances can be part of creating and partly controlling a technological nexus. The lead actors in the strategic alliance seem to be centres of translation and have a disproportionately large influence on the TN. The focus has changed to how a technological nexus might contribute in replacing a technology according to the conditions discussed in chapter three. The focus will not be solely on the TN but also on the roles of the centre of translation in the TN; the strategic technology alliance between BPS, Ford and DaimlerChrysler. The focus will be on how alliances have been used and how they can be used in the immediate future.

The fuel cell vehicle, an emerging reality or public relations?

Fuel cell producers, which are ICV manufacturers as well, might have hidden agendas. Making a strategy for fuel cells in trying to overcome lock-in barriers may not be what ICV manufacturers want. Developing fuel cell technology and being in front of development may be to position one in the best possible position before negotiating environmental goals, while the hidden agenda is to exploit the ICV profits as long as possible. Operating with an explicit double agenda may be a bit to extreme for reality, if one considers the amount of manpower and money put into the projects. The four largest Japanese companies have invested US$ 546 millions (DaimlerChrysler 1999), while the "Alliance" has invested close to a billion US$ by themselves. Kalhammer (et al.1998) estimates that between 1,5 and 2 billion US$ had been spent and committed on fuel cells globally up until July 1998. Additionally DaimlerChrysler expects to spend another billion US$ from year 2000 until expected commercialisation in 2004 (DaimlerChrysler 2000). In a race towards being first to market, other developers would also have to spend significant sums of money[33].

Ohi (2000: 1-2) claim that there are no major technical problems for building an infrastructure necessary for FCVs. Additionally; car manufacturers and the energy industry claim that they

[33] Unless imitation strategies are successful used as a means to manufacture FCVs.

are technically capable for the upcoming fuel cell vehicle and infrastructure requirements. Co-ordination and capital investments are still problematic areas though. Technical difficulties surrounding the FCVs are still problematic, even though Ohi claimed that vehicle and infrastructure problems could be solved. There are still several problems with the FCV that need to be dealt with before a market introduction (Srinivasan 1999: 315). BMW was previously the only major car manufacturer not involved in FCVs development, and identified several problems. Large scale manufacturing of FCVs was expected to have some difficulties. The efficiency results often ascribed to fuel cells remains to be achieved in regular production. Theoretical results and results under perfects laboratory conditions are quite different from achieving those results during production. BMW considered the unknown price of FCVs being a problem, and did not seem to support other car manufacturers optimistic conclusions (Maruo 1998: 50). As BMW later entered into the FCV arena (Avadykian et al. 2000: 38), the risks of staying outside fuel cell development is likely to have been perceived as to large. This implies less perception of risk in FCV development.

The major car companies invest only a part of its R&D budget on fuel cell technology, and most of the R&D budget is spent on the development part, that is new product development and not much basic research (Steinemann 1999:9). In this context GM, Toyota, Ford and DaimlerChrysler all invest heavily in research on fuel cell technology. In the car industry, technological change and innovation have always been important factors on the competitive arena (ibid:10). The car companies have previous experience[34] that gives them incentives to avoid lagging behind technological development that can favour fuel cell development.

Individuals and groups that made their careers on ICV technology in the auto industry can be expected to be more likely to put forward powerful resistance towards new technology. Some of the developers may have an interest in prolonging the introduction time of FCVs. Delaying the introduction time can be difficult when all the major players have estimated the first commercial release around 2004 and 2005. How long will developers dare to wait, considering the trade-off between first mover advantages and risks of technical and commercial mistakes? There is also a question of knowledge and competence involved with release of new technologies. If it is very hard or expensive to produce a second or third generation FCV without experience from the previous generation(s), then the entry costs may be to high to enter. The entry costs in the car industry are already very high, and seen as a reason why there has not emerged any new major car manufacturer in the last 30 years (Payne & Katz 2000). The costs involved in fuel cell development are rather large, which indicates that falling behind can make later entry hard. Thus imitation and late to market approaches become risky strategies, which give incentives for early investment in FCV technology.

DaimlerChrysler and BPS believes that the first actor to produce a FCV ready for market introduction will be able to set the rules for FCV competition (Panik 1998:37). Assuming the statement is correct, being first to market is important for that arena. Setting the "rules of the game", can be considered to be an OPP in relation to market introduction and competition. Operating with a hidden agenda might have to high costs if it forces the "Alliance" to adhere to other actors' solutions. If it is true that the first company that has a successful commercial launch set the rules[35], than competition cannot be expected to slow down. Unless there is an overall industry cooperation, the hidden agenda of delaying market introduction may be too costly. Toyota and Honda has announced beliefs about being first to market with FCVs, and Ford has a goal of being the environmental leader among the auto manufacturers (Kalhammer 1998 & Maruo 1998:7). If the companies' goals are more than public relations and reflected in further investments and support, than technological development would be expected to keep up the speed towards market introduction.

Critics of FCVs often state that car companies are likely to take an awaiting position. But the historical development of FCVs shows that this has not been true. Auto manufacturers that have been able to recognise FCVs as a possible solution have increased their investment in the technology rather than awaiting the situation (Steinemann 1999: 31).

To end the discussion of the FCVs possible introduction, the fuel cell panel's (Kalhammer et al.1998) conclusion will be presented. The fuel cell panel's conclusion states with cautious optimism that a FCV market introduction is likely. The main reason for considering it likely, is the strong interest taken by strong actors like Ballard, Ford, DaimlerChrysler, Toyota, GM and different agreements and projects that are active in promoting fuel cell technology.

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[34] The American car industry is generally seen as falling behind by Japanese car production methods in the eighties and had severe problems in adapting to the new production methods (Freeman & Soete 1997:141).

[35] Or more correct: if the companies involved with automotive fuel cell development perceive that the first actor on market set's the rules- a reinforcing process towards market introduction is started.

In the two years that have passed since the release of the Kalhammer (et al.1998) report, a number of new actors and arenas have emerged. Kalhammer (ibid) was optimistic to FCV development because of the enthusiasm among the car manufacturers and the joint projects. The emergence of more actors that are heterogeneous and several new projects can escalate the belief in a FCV market release. However, there are still several obstacles in relation to FCVs, and it is not cynical to question whether the FCV will emerge as a car for the future. As future development is unsure, the exact timing and number of released vehicles for the market introduction is unsure.

How can a technological nexus contribute to conditions necessary for escaping a lock-in?

How a technological nexus can help technological succession and how alliances can be used to control the nexus are the questions of importance in this chapter.

Necessary condition 1: A technological progress, which makes the technology competitive on quality and price.

The main members of the "Alliance" have achieved large technological breakthroughs, and are still working on price-cutting and integration. The "Alliance's" joint ventures produce knowledge as well as products, and the knowledge is likely to diffuse to the mother companies. The capabilities required for full-fledged automotive fuel cell development are many; few companies have either the finances or capabilities to go at it alone. A connection of several companies' core capabilities may be a prerequisite for developing FCVs. Joint efforts allow for parallel project development, and testing of several advances. A better product can be expected if knowledge is diffused to the cooperating parties. The "Alliance" has enrolled several car manufacturers into fuel cell development through licensed technology. The "Alliance's" FCE configuration probably diffuses from the lead actors in the technological nexus to some of the other actors. The fuel cell knowledge diffusion might occur through BPS sales of fuel cells stack to most of the major fuel cell developers and presumed reverse engineering on the stacks. Knowledge diffusion is also likely to occur through BPS fuel cell buses on trial periods. Regular innovation diffusion processes like proximity and movement of personnel between organisations is a likely factor to increase fuel cell competence among actors.

Historically we have seen that major breakthroughs in automotive fuel cell development have appeared from different arenas. A higher number of actors like companies, research labs and intermediaries as knowledge may provide more clues to problem-solving processes, and help create better technological solutions. Psychological fears about new vehicles was argued to have significance by Larbaoui (2000), and the fear could be expected to be moderated if the major car companies gathered into the technological nexus and promoted the FCV. Several recognised brand names are likely to reduce some of the psychological uncertainty. A market breakthrough for fuel cell cars would probably be much harder for FCVs if their commercial market release coincides with introduction of EVs. Two alternative propulsion technologies competing against each other would create uncertainty about which technology were to dominate, and make people await a dominating technology. Most of the EV producers are connected to the FCV manufacturers, s situation of competing technologies can more easily be avoided, than in other industries with different camps supporting different technologies.

Condition 2: Economics of scale is necessary to compete on price and the other competitive dimensions

The manufacturing capability necessary to achieve economics of scale is technically easy to obtain, as both Ford and DaimlerChrysler are experienced mass manufacturers. With a technological nexus pushing a FCV configuration, the critical mass necessary for commercialisation may be reached easier. The problem is that produced vehicles need to be sold, and grand-scale mass production needs to have a market. Enrolment and mobilisation of the network may create a general fuel cells interest in society, giving a kind of informational advantage, which can increase demand of FCVs.

Gagnon (1999) pointed out that the establishment of a dominant design is an important step towards a FCV introduction. It can allow first and second tier suppliers to produce greater quanta’s. A technological nexus can define a dominating design easier than single companies. How actors act within the nexus will decide their influence on the dominant design. Powerful arenas are expected to have more influence than small actors and arenas. In the “Alliance”, BPS is supposed to deliver fuel cell stacks to Ford, DaimlerChrysler and possibly other companies. Ballard Automotive is supposed to sell integrated fuel cell engines, and if the "Alliance" has managed to establish a dominant design production numbers could be higher. Ballard Automotive can supply several companies with an integrated solution, and sales can be higher if the "Alliance's" FCE configuration does not have to compete with other configurations. In this context, enrolment of auto manufacturers dependent on integrated FCEs becomes an important strategic factor. If one FCE configuration is allowed to receive increasing returns to adaptation, chances are that it will receive cumulating benefits, which makes it less susceptible to competition from other configurations. One specific configuration created trough a TN can be established easier than among several competing configurations.

Condition 3: Discontent with the embedded technology on one or more points, which provides the new technology with some kind of improved performance compared to the established technology.

The "Alliance" has some impact on changing the public opinion on the issue of cars, on the reasoning that Ford and DaimlerChrysler are two of the major car producers. On issues about human climate, the big three car companies in USA, fiercely resisted scientists' acclaims of the need for CO_2 reduction. But the European car producers accepted the claims and started working on it, and later the big US companies also changed their strategy (Levy & Rothenberg 1999). If the alliance is able to enrol other actors as states and environmental organisations, the alliance's power may increase. Support and claims about disapproval of old technology can be accompanied by positive publicity about the new technology. Most of the car manufacturers are now working with governments, probably in order to easier gain influence. A positive side-effect for companies is the governmental goodwill they receive by being proactive on environmental concerns, that goodwill can make it easier for companies in later negotiations. Discontent with a technology has strongest effects when several heterogeneous actors support it.

Policy and taxes also play a part, because if some companies are able to deliver a more environmentally sustainable product, than taxes (on ICVs) and other incentives to produce/drive FCVs can help introduce new technology. Different governments are already involved with fuel cells, probably because it is a politically easy way to reduce CO_2 emissions, and the enrolled legislative judiciaries can be helpful on the way to the market. The emotional aspects of gasoline and its price must be considered if governments were to try raising taxes to facilitate FCV introduction. The civil disobedience in Europe September 2000, in response to high gasoline prices, showed the extent in which the ICV network has enrolled large parts of society. Raising taxes to give incentives for abandoning the ICV may also meet with similar opposition. But an alternative perceived as substitutable and with superior performance on cost of driving may limit the ICV network's complaints.

An extension of the strategy framework is particularly helpful, since actors outside alliances usual reach can be central actors. Environmental NGOs can play powerful parts in dissociating existing technologies from consumers and governments. The NGOs and trends in society also influence the business environment and the impact of "green" issues in business has increased (Foster & Green1999: 3) making life harder for regular ICV production. An important aspect, as often pointed out in ANT is that enrolment of actors is never stable. With the case of NGOs, companies can try to enrol them, but the NGOs may break out and pursue other goals, which are conflicting with companies' interests.

How can a technological nexus contribute to enabling conditions for escaping a lock-in?

Enabling condition 1: providing compatibility with established technology

Before FCV technology can become known, several choices regarding technological solutions have to be made. Choices that make FCVs easily compatible with ICV technology, can enable the technology to take advantages of existing network advantages. In the USA a 100 billion US$ have been spent and 10 billion US$ are spent annually to uphold and advance the ICV and its socio-technical surroundings (Maruo 1998:19). When amounts like that are being spent on the ICV, it obviously makes sense to enable a new technology to gain advantages from it. In relation to fuel cell technology the road infrastructure, can provide gains without much extra cost. Nexus participation by actors such as Shell and MobilExxon, BP and Statoil enables better searches for solutions that are compatible with the existing infrastructure, which the mentioned actors can provide. The whole value chain of the oil companies can be of use, from transport and refineries to the filling stations, and it can ease the eventual transition to FCVs.

Establishing a dominant standard has been identified as a necessary strategy for developing an alternative propulsion technology (Gagnon 1999). There will always be some differences in integrating FCEs into the rest of the machinery for different producers. Establishing different standards and solutions, across the industry, that capitalises on compatibility are probably useful for FCV introduction. The “Alliance” can make their solution, but other manufacturers might challenge it with their own solutions, contributing to different solutions and awaiting customers. Enrolment of several other actors like gas companies makes it easier to cooperate on a solution thereby not wasting resources. Two emerging problems could be monopolistic competition and risk of being locked-in to another less than optimal technology.

Several technical issues, especially the fuel issue remain an open question. The choice between Hydrogen, Methanol and gasoline has numerous ramifications for a FCV. The involved actors have different viewpoints. Kalhammer (et al. 1998) pinpointed Methanol as the fuel solution, and all the major car companies are working on it. Hydrogen is perceived as too costly and difficult while gasoline is not good enough for environmental concerns. Recently GM and MobilExxon (GM 2000) have developed the gasoline option further. Hydrogen still has its advocates with, Toyota and DaimlerChrysler, which have Hydrogen experience. Methanol is usually regarded as the best option, but other possibilities exist. New technological developments and experience might change the favoured option. As technological compatibility is considered important, a conflicting solution for fuel is not optimal in relation to market introduction. Strategic alliances can strengthen the social power of a technology by companies joining and favouring one specific configuration. If the TN can provide technological compatibility between the differing FCV configurations and create an industry standard, then market introduction is more likely to be successful. But if the “wrong” configuration is selected or emerges through the nexus, optimality is lost once more.

An additional (corporate) advantage from enrolment of governments is that government funding of infrastructure could be considered a subsidy. Product subsidy is mostly illegal (at least in the developed countries) while subsidising a technology trough its infrastructure usually falls outside the legal issues. This will of course favour the products that grow stronger as they become more entrenched in society with government credibility and financial support.

Enabling condition 2: Limited increasing returns for the embedded technology

It will always be tough for a new technology to emerge if the existing technology is receiving what Arthur (1988) called increasing returns to adaptation. So the important question is, how can a technological nexus limit the embedded technology's increasing returns?

The process of limiting the returns for the embedded technology reinforces itself when the new technology receives increasing returns itself. When a new technology takes market shares from the established technology, it gets a double effect by gaining power and weakening the competition at the same time. As a FCV market introduction probably will vary according to regions as pointed out by Honda (in Kalhammer et al. 1998), the new technology has the opportunity to gain strength and reputation through market experience related to the varied commercial releases. As FCVs are released in one region and environmental demands are increased, the FCVs manufacturers have the advantage of new governmental demands being set in the regions to be approached later, that is if the technology proved feasible.

Enrolment of actors that have the ability to influence demands and regulations are important in the TN. CARB has proven to be a vital actor in the FCV arenas of development. CARB requirements as well as CAFE standards have changed the industrial requirements, and limited the returns on ICVs because of increased cost related to technical difficulties. Other governmental interventions and policy regulations have also contributed in changing car requirements. CARB and CAFE regulations have given incentives for an environmentally sustainable vehicles. CARB has put pressure on the car industry to produce cars that emit less CO_2. Through intermediaries like laws, they have forced (enrolled) other actors into development towards their goals. Governmental agencies like CARB has proved essential in the TN, because "pure" political and regulatory power now can be used to enrolment of new actors, and interessement by crafting harder conditions for the existing network.

Enabling condition 3: State regulation, as well as other kinds of regulations might present advantages to new technology

When the technology development is in the auto industry, the hidden agenda issue is a bit tricky, because the car manufacturers finance their own competition. All automobile producers have yet to make profits on FCVs, and are some years and large investments away. Companies involved in fuel cell development, without being connected to the ICV industry, have incentives to limit the profits on regular ICVs. A technological nexus that has enrolled environmental agencies and other public authorities might be able to put limits, restrictions and taxes on the existing technology giving the new technology better opportunities. The heterogeneity amongst the actors is likely to play a part in demanding state regulations.

The governments of Canada, USA and Iceland are enrolled in the FCV nexus. Canada has supported Ballard and cooperates with them on a bus project. USA is involved through CAFE, USCAR, CARB and the Fuel Cell Vehicle Project. Iceland wants to reduce and change the diesel engines in its fishing fleet, and have chosen to participate with the "Alliance". Iceland has involved itself in a feasibility study of fuel cell busses on Iceland and a pilot project involved with Hydrogen production (Maruo 1999:15). The " Alliance" is participating in the Iceland project, and exemplifies how the "Alliance" uses (what Maruo called:) intergovernmental alliances to enrol and mobilise new actors towards the creation of a stronger technological nexus. With "Alliance" buses as intermediaries in the Iceland bus project, the technology and knowledge may be localised and made tacit in Iceland. Thus Iceland has the "Alliance" configuration as a starting point. The informational increasing return to adaptation argument was based on: the more actors know about a new technology, the higher the likelihood of using it. Involving a government into FCV projects can be seen as educating them to be continued users. Enrolled governments can present favourable legislation for the introduction of FCVs.

On a higher level an international regulatory framework is being built. An international agreement on global vehicle regulations became effective from 25.08.2000 under the UN umbrella (XINHUA 2000). The agreement only has eight members: Canada, France, Germany, Japan, UK, USA, EU and Russia, but he major car producing countries are involved. An international forum has the possibility of discussing and changing regulations easier than the countries can do it single-handedly. Experiences with FCVs may diffuse easier from a region to another with an international forum. Actors as these just mentioned are often centres of translations themselves and may not be easily enrolled. If an international forum recognises the ICV as a problem, and identifies FCV vehicle as the solution, FCV commercialisation may fare easier.

Enabling condition 4: The availability of niche markets facilitates learning and improvement in friendlier environments.

Strategic niche management was presented as a strategy for technological succession; but was not chosen to be the focus of this paper. The creation and sustainability of niche markets are likely to have some connection to the technological developer(s). It might be hard for a company to develop a protected niche market alone, because interaction between technology, the environment and consumers play important roles. A company can of course be able to do it by themselves, but by taking the TN as a strategic starting point there are extended and better possibilities.

Enrolment of several other heterogeneous actors increases the possibility of receiving feedback on all dimensions of the new technology. Feedback from different sources is usually better because the technology gets tested under different circumstances, contributing to locating different problems. Several fuel cell bus projects are already implemented, and BPS has started putting the first of 30 busses into circulation around the world (Ballard 2000). Cities are figuratively speaking, lining up to get a couple of fuel cell buses at a cost five times higher than a regular bus (which is partly about trends- upcoming discussion) (ibid). Using alliances to enrol actors to test out the new technology is a way of increasing the public awareness about the technology as well, so it has double effects.

The project in Iceland exemplifies what can be gained trough development of niche markets. Iceland's specific geographic climate can present specific learning advantages that might be useful. The harsher climate provides good conditions for exploration and learning of the weak points in the FCV technology. A "live" project has the advantage of testing all dimensions of a new technology. The scientific base will need to prove its efficiency in real life situations. The technical dimension will also have to be dealt with, new and unexpected problems are likely to emerge in a niche projects. The social dimension will play a part as "regular" users enter the arena and interact with the technology. Infrastructure, technical and people might create problems with the technology, as the problems are identified, a search for solutions can start. Niche markets allows exploration of the three dimensions of technology in a "secure" environment, and they can easier be facilitated within a nexus.

Enabling condition 5: New trends might favour new technology

The TN can be considered to have three dimensions, and an interesting question is how trends can influence them. Trends influence consumers and trends, and more specific trends influence researchers, developing engineers, companies and research institutions. How the technical and scientific trends have influenced, and can further influence FCV development will be discussed.

The fuel cell community[36]grew steadily from 1974 to 1984, but from 1984 to 1996 the number of members rose from 400 to 1800 (Schaeffer & Uyterlinde 1998: 257), which indicates a growing interest in fuel cells among researchers[37]. As the hype has grown larger since 1996 trends can be expected be more favouring to fuel cell technology. The general impression of FCV development is that more and more heterogeneous companies have become involved with fuel cell development in some way or other. The gradual increase in the "fuel cell community" and the increase of companies involved, indicates a strengthening of the TN.

There are no specific "strategic intentions" in the "Alliance" to influence trends[38], but two of the largest car companies' choices have certain snowballing effects. If companies like GM, Toyota, Ford and DaimlerChrysler offer career opportunities to newly educated personnel with training necessary for fuel cell development, those scientific or technical disciplines are likely to increase their popularity. One could expect more engineers and scientist to get an education in that area. As the TN evolves with universities and other institutions, better educational and training facilities and an increase in professional personnel can be expected. In the evolution of the TN, choices made in important strategic alliances can be used to guide

[36] The fuel cell community can be defined as the number of people who wrote an article about fuel cells that year, and also had written an article on the subject no longer then two years earlier
[37] But, the overall interest of science and technology, and also non-nuclear science have increased a lot, which levels out some of the increase in fuel cells specifically.
[38] There are intentions of influencing trends, according to my knowledge. But I consider it likely that marketing divisions within, Ford, DaimlerChrysler, GM and Toyota have given it some thoughts.

the nexus in a specific direction. As an example: the “Alliance”’ choices can be considered market signals not likely to be ignored by the surroundings. The choices taken by the “Alliance” have the potential of creating trends in technological development, as seen with the introduction of NeCar 1 and the cooperation between BPS and DaimlerChrysler.

Enabling condition 6: Scientific results might influence regulation, policy and adaptation of new technology.

Science has played a large part in fuel cell development, and in the development of a technological nexus. Scientific discoveries made by LANL and BPS changed the worlds perception of fuel cell technology, and gradually legislation and subsidies favoured fuel cell research.

The greenhouse gas emissions activated a search for alternatives and started a discussion about the use of ICVs. Science may be considered the starting point of change, since a consensus about reducing CO_2 emissions came from science. Science involved institutions as media, governments, and NGOs throughout the world. US car companies previously fought and denied the reliability of the scientific reasoning for reducing CO_2 emissions. That approach has ended (Davy & Rothenberg 1999), as the beliefs of science proved too hard to contradict for the car manufacturers. The auto manufacturers were fighting science at two frontiers, one front of the mentioned demands about CO_2, and a FCV frontier that implied possibilities for large emission reductions. Science was and is important for the development and strengthening of a FCV nexus. The number of research institutions involved with fuel cell development is high and can be seen in appendix b. Scientific institutions are contributing to FCV development as specialists in collaborative agreements.

Concluding remarks

A technological nexus consistent of a multitude of heterogeneous actors are of importance for the development of a technology. Joint technological development through alliances and the creation of a technological nexus has been of significance in relation to some of the conditions necessary for escaping a lock-in. The creation of a nexus has particular importance in relation to the first two necessary conditions. The nexus can contribute in developing a technology, which is competitive on quality and price, because it relates to all dimensions of the technology. Cooperation with specialist firms on all aspects of the technology and diffusion of knowledge throughout the nexus has contributed in developing the FCV technology. The new technological alliance with BP, Methanex and Statoil pursues the development of a Methanol infrastructure and its requirements, and is a good example of expertise enrolled into the network. The second necessary condition regarding economics of scale in a technological nexus is also of importance. Involvement of all the major car manufacturers can also play an important part in the future by reducing psychological uncertainty about the new technology, thus make market introduction and achieving economics of scale easier to achieve.

Among the enabling conditions, the technological nexus is apt to have strong impact on the first and fourth conditions. The TN can increase compatibility with the ICV network and compatibility among the actors involved in FCV development. Compatibility can assure FCV configurations that are able to use the same infrastructure, thus provide network advantages.

The creation of niche markets or enrolment of niche markets into the TN can also play an important part, as it allows for testing and learning advantages of the technology under real conditions. Although a nexus can contribute on other points, this is where its influence is most significant.

6. Conclusion

Introduction

The main intention with this paper was to explore technology dynamics, especially how lock-in could be superseded and if strategic technology alliances could play a part by creating and strengthening a technological nexus. An extension of strategy with STS perspectives seemed useful in understanding the development of fuel cell technology. Technology development, introduction and substitution have hard strategic issues to resolve. Nevertheless it is important for the companies who invest up to several hundred millions US$ in a new technology, to have some ideas about issues related to the techno-economic network.

Technological development and strategy

Alliances have become almost the norm in fuel cell development (Avadikyan 2000: 40), and have played important roles in building a technological nexus. Most of the car companies are involved in alliances, and some of them are directly connected, but partial connections have also played major parts in the creation of a technological nexus. The major auto manufacturers play important integrating parts in fuel cell development, together with specialised partners. The importance of path dependency has been shown, as the important FCV actors today, are the actors that have been involved with the technology since the reopening of FCV arenas of development. Alliances can be considered as playing important parts in the creation and strengthening of a FCV technological nexus.

Partial connections like CARB, CAFE, California Fuel Cell Project and USCAR have connected previously unconnected parts of the network, thus allowing knowledge to diffuse easier through the different arenas of development. CARB have played an especially important role and provided incentives for all car manufacturers to develop more sustainable cars. It is interesting to note that CARB is a state level agency and not a federal agency. It shows that in a network the most effective promoters of change not necessarily are of the highest level of government, but that lower levels can be equally capable of promoting change.

Alliance strategies within the technological nexus have been discussed. The “Alliance” has used strategies like openness of technology and enrolment of other actors as strategies to promote their FCV configuration as the technological solution. The “Alliance” has developed strong relationships that develop resistance to opposition, by being involved in an increasing number of company and inter-governmental alliances[39]. The “Alliance” has established itself as the “centre of translation”, because it is connected with several arenas of development, and has “authorship” in many of its alliances and agreements. The strategy of creating a technological nexus to can be considered helpful. A TN is able to promote an emerging technology, in relation to the necessary and enabling conditions for technological change.

Further directions for research

Further developments can go in three directions from this paper. How to escape a lock-in failure can be investigated further. The ICV and incandescent lightning are the most used examples to investigate lock-in, examination of other technologies could prove interesting. Less recognised technologies, prominent in certain areas of production could yield insights to the lock-in phenomenon and how to escape it.

The integration of strategy and socio-technical issues can be developed further. As strategy play a major part in technological development, it should not be left so unconsidered as it tends to. Ideas about random and uncontrollable processes of innovation have been taken too far, and strategy can provide relevant perspectives. Additionally, strategy can expand positively, by integrating technology dynamics into the field.

The future development of FCVs is likely to experience more research as market introduction comes closer, as commercial entry is planned in four to five years. The road towards market introduction provides nice opportunities to study technology dynamics, in relation to technological change. Interesting research opportunities lies in the processes towards fuel cell

[39] In the period of writing this dissertation the “Alliance” has joined new agrements, which supports BPS and DaimlerChryslers stated strategy of using alliances to achive a good product. On the 13.09.2000 they signed an agreement evaluating Methanol as a fuel, incorporating new actors (Methanex 2000). On 27.09.2000 another agreement is signed with QuestAir Technologies Inc, this agreement focuses on purification of the fuel process, allowing weight and cost reductions (BPS 2000).

market introduction. How the ICV network will behave towards market introduction of FCV is also an interesting question that deserves attention. The debate between the cynical and the optimist points of view on the issue of corporate forces in relation to environmental technology can be concrete in relation to FCV development. Will corporate forces and technology solve environmental problems, or will they back out somewhere in the process towards commercialisation? The next few years can give interesting insight into the nature of companies, technology development and corporate environmental slogans. The cooperation in the "Alliance" and its network seem to go smoothly, but another interesting research topic is how the relationships will change (if at all) towards competitive market introduction.

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Appendices

Appendix a: methodology

Origin of ideas

The choice to focus my topic on development of automotive fuel cell technology was taken in Strasbourg at the research laboratory Beta. Beta was involved in research projects TSER and TIPIK, concerned with alliances and fuel cell development. The idea of looking at necessary conditions for escaping a lock-in failure of the existing technology was given to me by the ESST co-ordinator at Beta, and my counsellor Patrick Llerena. Combining alliances, fuel cells and how to escape a lock-in failure became the issues to be integrated in this dissertation.

In relation to TIPIK, interviews were to be done at DaimlerChrysler in Germany. Interviews were already done with the French auto manufacturers. Unfortunately, DaimlerChrysler was slow at responding and interviews were done after my departure from Strasbourg. After interviews stopped being an option, bibliographical research was chosen to be the methodology of this paper.

Bibliographical research:

In the quest for relevant literature the databases: " Science Citation Index Expanded™", "Social Sciences Citation Index®" and "Arts & Humanities Citation Index®" were the main instruments for bibliographical research. The databases: EconLit on the Webspirs (Silverplatter) and "ECONbase" were also used in the search for literature. The ISI databases were by far the most useful instruments in searching and finding literature.

The bibliographical search on the relevant issues turned out less then optimal and it was generally hard to find relevant articles. It was especially hard to find relevant articles about the development of fuel cell cars. However the amount written on fuel cells is large, mostly technical papers though.

Often the rewards of bibliographical searches were limited, an example is Cowan & Hultens article (1996) "Escaping Lock-in: the Case of the Electric Vehicle" which is very relevant to my topic even though the article is old. An article on lock-in, published four years ago resulted in one cited reference only, which indicates the small amount of literature on the topic. Other interesting articles generally did not have many references, and when they did a circle of referenced articles was often the end result.

Sources contradicting other articles are remarked upon in the main text, as Windrum and Ohi's texts are. The sources: "Xinhua", "Canada News Wire" and "Payne and Katz" are gathered trough a internet automobile news source, and their credibility can not be approved, even though I have no reasons to expect otherwise. Some sources proved especially valuable for understanding technological development: Maruo (1998), Kalhammer (et al. 1998) and Steinemann (1999), more recent material about FCV development was only found on the web. Other recent articles are in French, thus considered unavailable for my use, and the book by Cowan & Hulten (2000) was not in sale by the delivery date for this dissertation.

An end remark to the bibliographical search, the process of finding relevant literature was hard and time consuming, but provided (hopefully) enough literature to have a serious and relevant discussion on the topics of my dissertation.

Generalisation

To generalise from this study of fuel cell technology to other new technologies facing incumbent technologies is hard, and maybe not advisable. The auto industry is dominated by relatively few players (about 20 OEMs), which make it hard to generalise from findings on technological development and alliances. Seven of the worlds 10 largest companies are involved with fuel cell development, and all those seven companies can be expected to have budgets and political power on the same level as small and maybe medium size states.
Industries, which have a more diversified structure, may have different dynamics for technological development than the centralised auto industry.

Lack of empirical results

The lack of empirical collections in this paper, has limited the value of this dissertation. To discuss the use of strategic alliances, there are strong drawbacks in lack of knowledge. As automotive fuel cell development is surrounded by secrecy, many strategic issues are not discussed or published openly. Secrecy and strategic considerations have increases the difficulty of gaining access to material regarding automotive fuel cell development (Maruo 1998:40). The lack of material on other alliances than the "Alliance", was especially limiting for discussing different use of alliances. An important question is whether this reflects the "Alliance" position and its strategies, or if the skewed information has led to a misinterpretation of fuel cell technology development? Would more open strategies and less secrecy among the other companies have made the conclusions different? As the "Alliance" is generally regarded the technological leader in automotive fuel cell development, I think that the findings reflects the "Alliance's" position rather than reflect skewed information. Nevertheless, interesting aspects regarding control and power inside the nexus were lost. This is neither the first or last paper in strategy that focuses on the strongest actor of that time, and possibly underestimates other actors involved, but it is still an inadequacy for this paper.

To be able to answer the questions asked about the use of alliances in this paper, extensive interviews and or observation (shadowing) of corporate boardrooms have the potential of finding interesting empirical results. The strategic considerations taken at the highest levels of the involved corporations are important. Whether a student at master level would have been able to gain access to top management and scientific personnel is not likely. Whether strategic considerations would be discussed openly at all is interesting as well, so in this relation shadowing would be likely to provide more reliable information than interviews. It would be my guess that this kind of information would rarely leave corporate boardrooms, but trying to answer these issues in more details are important and intriguing questions.

Significant articles and other sources of information have been found, providing useful information about company strategies. Although additional company information would have been positive in some cases, but enough material is collected to provide an understanding of the investigated issues. It is my hope that the literature collected as worked as a foundation for understanding of strategy and socio-technical relationships in relation to technological development.

Theoretical criticism & considerations

Strategy and AoD/ANT have been used as theoretical framework in this dissertation, and the attentive reader noticed the lack of criticisms of those theories. There appeared no theoretical criticisms because it is not an interesting thing to do. If this had been a theoretical paper, a thorough criticism and discussion would have been required, but as it is, not I preferred to use the available space to explore technology dynamics. Additionally, I presume that ANT has been criticised a number of times in ESST dissertations and another repetition is unlikely to be particularly useful. The vast field of strategy was to large to be presented thoroughly, which would have made criticism and discussion of it hard, but Mintzberg's book (1998) provide good presentation of the strengths and weaknesses for the different schools of strategy. It is not particularly interesting for me to criticise AoD either, although not much has been written about it. One aspect AoD could be criticised for is if Academia really needs another concept for understanding technological change, or could ANT or other notions concerned with technological change have been used? AoD was chosen, because it seemed more structured than all the diverging directions in ANT. All the divergence and theoretical complexity related to ANT has a certain context and confusion, which I did not desperately wanted to connect with this dissertation. AoD, had the positive aspects of ANT regarding flexibility, which is lacking in other theoretical frameworks, hence AoD was selected.

AoD and ANT are usually used to enlighten phenomena's from the past. Automotive fuel cell development is an ongoing project with several possible pathways, which make use of those theories intricate. The development of FCVs is still an unpredictable project, which can go several ways, and successful commercialisation is in no way ensured. The issues surrounding commercial release are many and complex and involve companies, NGOs, governments and consumers, in which all actors can interfere. Stories about fuel cell development can be written in 2010 with greater certainty, but the strategic considerations are important today. The point I am making is simply that any analysis made today may be ridiculed in hindsight two years later. I do not intend to predict the future, but discuss possible future occurrences in order to explore those possibilities with strategy and STS matters.

Appendix b: abbreviations and acronyms

AoD: Arenas of Development

ANT: Actor Network Theory

BPS: Ballard Power Systems Inc.

CARB: California Air Resources Board

CAFE: Corporate Average Fuel Economy

EV: Electric Vehicle

FCV: Fuel Cell Vehicle

GM: General Motors

HDTV: High Definition Television

HEV: Hybrid Electric Vehicle

ICE: Internal Combustion Engine

ICV: Internal Combustion Vehicle

LANL: Los Alamos National Laboratory

LEV: Low Emission Vehicle

OEM: Original Equipment Manufacturer

OPP: Obligatory Passage Point

STS: Science and Technology Studies

SULEV: Super Ultra Low Emission Vehicle

TEN: Techno Economic Networks

TLEV: Transitional Low-Emission

TN: Technological Nexus

ULEV: Ultra Low Emission Vehicle

USCAR: United States Council For Automotive Research

ZEV: Zero Emission Vehicle

Appendix c: involved actors

The number of actors involved with fuel cell development is changing rapidly, and this is not an extensive or thorough list, but a list to show the heterogeneity amongst the actors constituting the FCV technological nexus. Even though not all actors ion the nexus is mentioned, the list show the magnitude of institutions involved:

Acumentrics Corporation
Aluminum-Power
American Hydrogen Association
Anuvu Incorporated
Argonne National Laboratory's Fuel Cell Section
Astris
Avista Laboratories
Ballard Power Systems
BCS Technology, Inc.,
California Fuel Cell Partnership
California Hydrogen Business Council
Case Western Reserve University, Ernest B. Yeager Center
Celsius
Ceramatec
Ceramic Fuel Cells Ltd
Consej Superior de Investigaciones Cientificas
CoPower.com
Coval H2 Partners
CSIRO Energy Technology,
DaimlerChrysler
DAIS Corporation,
DCH Technology, Inc.
DE NORA s.
Desert Research Institute,
Dias Analytic Corporation
Distributed Power Coalition of America
dmc-2
Draeger Safety,
DTI Energy, Inc.
EBARA Ballard Corporation,
EcoSoul
Edison Technology Solutions
Electric Auto Corporation,
Electric Power Research Institute
Electro-Chem-Technic
ElectroChem, Inc.
Element 1 Power Systems Inc.
Elf Atochem Energia Ltd.,
Energy Partners, Inc.
Energy Partners, L.C.,
Energy Related Devices
Energy Research Corporation
Engelhard Corporation
E-TEK, Inc.,
ETH Ceramics
Evonyx
Federal Energy Technology Center
FEV Motorentechnik GmbH
Federal Energy Technology Center's (FETC)
Fuel Cell section
Florida Solar Energy Center
Forschungszentrum Julich
Fuel Cell Commercialization Group
Fuel Cell Group
Fuel Cell Technologies, Ltd.,
FuelCell Energy, Inc.
Gas Research Institute
Gaskatel GmbH,
Gaz De France
GE Energy and Environmental Research Corp.,
GE MicroGen
German Hydrogen Association
Giner Inc.
Global Thermoelectric Inc
H Power
Heliocentris Energiesysteme
Hitachi Works,
H-Tec - Wasserstoff-Energie-Systeme GmbH
Hydro Quebec Research Institute,
Hydrocell U.K
Hydrogen Information Network - Department of Energy Hydrogen Program
Hydrogenics Corporation,
Hypercar Center by the Rocky Mountain Institute
ICTP-CSIC
IdaTech,
IMPCO Technologies
InnovaTek, Inc.,
Institute of Gas Technology,
International Fuel Cells, LLC
Ion Power, Inc
Japan Automobile Research Institute, In
JLG Industries,
Lawrence Berkeley Laboratory,
Lawrence Livermore National Laboratory,
Los Alamos National Laboratory
Lund Institute of Technology
Lynntech, Inc.
Manhattan Scientifics Inc.,
Massachusetts Institute of Technology,

Materials and Electrochemical Research Corporation)
M-C Power Corporation,
McDermott Technology, Inc.,
Metallic Power
Mitsubishi Electric Corporation
Mitsubishi Heavy Industries, Inc.,
Modine Manufacturing Company
More Energy Ltd.,
Mosaic Energy
MTU Friedrichshafen
NationalAeronautics and Space Administration,
National Aerospace Laboratory
National Fuel Cells Research Center
National Hydrogen Association
National Renewable Energy Lab,
Netherlands Energy Research Foundation,
NexTech Materials, Ltd.,
Noguchi Institute
Northwest Power Systems
Nuvera Fuel Cells
Ocean Power
ONSI Corporation
Ontario Hydro Technologies
Pacific Northwest National Laboratory,
Partnership for a New Generation of Vehicles (PNGV)
Phoenix Fuel Cell Systems
Plug Power, LLC,
Procyon Power Systems, Inc.,
Proton Energy Systems
Refrac Systems, Arizona, USA
Rocky Mountain Institute,
Sandia National Labs
Schafer Corporation, California
Schatz Energy Research Center
Siemens AG,
Solar Hydrogen Energy Corporation
South Coast Air Quality Management District
Southeastern Technology Center
Southern States Power Co
Southwest Research Institute
StarTech
Stuart Energy Systems
Sulzer Hexis Ltd.
Sure Power
TATA Energy and Resources Institute
TNO Energy & Environment
Toshiba Corporation
Toyota Motor Corporation
U.S. Department of Defense (DoD) Fuel Cell Demonstration Program
U.S. Department of Energy Fossil Energy's Fuel Cell section
U.S. Fuel Cell Council
United States Department of Energy (Office of Transportation Technologies)
United Technologies Research Center
University of California-Davis' Fuel Cell Vehicle Modeling Program
VTT Chemical Technology
Warsitz Enterprises
Westinghouse Savannah River Company
Worchester Polytechnic Institute
Xcellis Fuel Cell Engines Inc.
ZeTek Power PLC, Zevco,
ZSW, Center for Solar Energy & Hydrogen Research,

(Sustainable Minnesota 2000 & Fuel Cell's 2000)