To be presented at the 10th international conference of the Greening of Industry Network
June 23-26, Göteborg, Sweden

Exploratory analysis of the transition towards fuel cell technology in the transportation sector: trajectories and actor perspectives

M.P. Hekkert, M. Meeus, E. Moors, J. Faber

Utrecht University
Copernicus Institute for Sustainable Development and Innovation
Department of Innovation Studies
Heidelberglaan 8, 3584 CH, Utrecht, The Netherlands

1. Introduction

Climate change is one of the major environmental threats of today. In order to mitigate the risk of climate change, the amount of carbon emissions should be decreased to a fraction of the current emissions (Houghton 2001).

The transport sector is an important sector in terms of carbon emissions. In 1995 the transport sector contributed to 22% of the global energy related carbon dioxide emissions. Furthermore, emissions from this sector are growing at a rapid rate of about 2.5% annually (Metz, Davidson et al. 2001).

In order to reduce the carbon emissions in the transport sector several technological options are currently available and being developed. Examples are electric and hybrid vehicles, lower weight structural materials and fuels based on renewable energy sources. One of the most promising options to increase the efficiency of road transport and thereby decreasing carbon emissions is the use of fuel cell vehicles (FCV). Automotive fuel cells have the potential to achieve twice the energy conversion efficiency of conventional internal combustion engines with essentially zero pollutant emissions (Metz, Davidson et al. 2001).

Currently, almost all major car manufacturers are working on the development of FCV's. A decisive factor for this development has been the zero emission vehicle mandate of the state California, which states that all car manufacturers that sell cars in California should introduce zero emissions vehicles in the year 2010. The size of the Californian car market is large enough to explain the high research efforts in this area.

A matter of choice is what fuel will be used to power FCV's. The choice is between hydrogen, methanol, ethanol, natural gas and traditional fuels like gasoline (Ogden, Steinbugler et al. 1999; Godfroij 2002). As will be explained in section 2, the choice has consequences for the design of the car but also for the fuel infrastructure that is necessary to make large scale diffusion of FCV's possible. Since the fuel choice has large consequences for the technology and organization of the future transport system, the fuel choice has major impacts for the transition route towards large scale implementation of

FCV's. Following Ogden, Steinbugler et al. (1999) we discern three transition routes that are currently regarded as the most likely options:

I. hydrogen as fuel for fuel cell vehicles
II. methanol as fuel for fuel cell vehicles
III. conventional fuels as fuel for fuel cell vehicles

At the moment we are standing on the doorstep of a possible regime shift in car engine technology and fuel infrastructure. In this paper we try to unravel processes governing this transition toward other fuels. First of all we introduce a general model of the co-evolution of technology and organization, second we develop a simple theoretical model of factors governing successful transitions.
We discern between the car manufacturers that are currently developing fuel cell vehicles and the other actors that have supporting roles in this development process or are important in the implementation process.

2. transition routes towards fuel cell vehicle based transportation system

A dual perspective of technology
Do technologies have a live of their own? Yes, in so far as they work on the basis of natural laws. No, in so far as they need to be developed, adopted and implemented by actors whose behaviors sidestep these natural laws and even supersede them. This simple observation is the key to our theoretical understanding of technology and innovation.

Here we take the following theoretical starting point. Technology is explored from a dual perspective (Podolny 1993; Podolny and Stuart 1995; Rosenkopf and Tushman 1994). One the one hand technology – either as an isolated artifact, or a system – consisting of a set of hardware and software components, and interfaces that make up a network of functions that allow the system to function. On the other hand for every component and interface a number potential producers / suppliers can be identified. This implies that an analysis as well as transition trajectories should account for the exploration of functions and quality of a technology, as well as the capabilities, skills and networks in the actor set producing and implementing the technology as such, and that functional technology relies heavily on the ability of the actor set to collaborate in an orderly and productive manner. Rosenkopf and Tushman (1994: 404) label this phenomenon as *co-evolution of technology and organization.* They imply that where choices between competing technologies are not obvious – there is no technical option that outperforms the other options – the dominant technological outcomes are more a function of the formation of organizational coalitions in the actor set. The assumptions on which this theoretical starting point builds are:

P1 Technical rivalry is often not settled by technical logic based on performance benchmarking.

P2 Social and organizational dynamics (formation of coalitions, breakdown of coalitions, political change, need determinateness of users) enlarge the set of criteria defining life chances of technical options (selection process) and result in the elimination of a subset of technical options.

P2.1 Organizations form coalitions on the basis of converging interests.

P2.2 Converging interests on their turn are based upon converging preferences for technical options.
P 2.3 Converging preference for technical options are either based on overlapping R&D activities, former business partnerships or complementary R&D activities or skills (Meeus, Oerlemans and Hage 2001)

Measuring potential adopters' perceptions of innovations has been termed a classic issue in the innovation literature (Tornatzky and Klein 1982; Moore and Banbasat 1991; Rogers 1995). Generally, the idea is that when potential adopters perceive an innovation as having many negative characteristics, e.g., complex, not compatible with current practices, and difficult to try out, the success rate of adoption and diffusion will be lower than when the innovation is perceived as having many positive characteristics. In most of the innovation studies that measure perceived innovation characteristics the potential adoption of an innovation by a homogeneous actor group is studied (Tornatzky and Klein 1982; Rogers 1995).
Studying the adoption and diffusion of FCV's is more complicated than for many other technology changes since system changes are required for two out of three FCV's (Diffusion of hydrogen and methanol FCV's can only take place when the fuel-infrastructure is adapted). This implies that many different actors need to adapt to the innovation.
Measuring the potential adopters' perceptions of system innovations therefore differs from other type of innovations. In the case of system innovations a wide range of different actor groups need to be included in the analysis. Furthermore, an extra dimension of perception is introduced. Not only the normal scale of **how** actors perceive the characteristics of an innovation is important but also the potential **heterogeneity** of actor preferences is important to assess the rate of diffusion of system innovations. We hypothesize that a large heterogeneity in actor preferences regarding innovation characteristics will slow down the rate of diffusion.

P3 The remaining options are subsequently compared and selected on the basis of a smaller more specific set of technical performance criteria that are shared and supported by the actors (stakeholders) in the coalition(-s).
P4 The stability of the coalitions is a function of the fit between expectations of technologies (Lente and Rip 1998) and the final selection for all involved actors, and the absence of new technological discontinuities.

In addition to this set of assumptions we should take into account the distinction between the evolution of systemic technologies and their actor sets as compared to 'simple technologies'. For simple technologies competing designs may be compared on straightforward measures such as price/performance ratios. Selection of a dominant design is based on these techno-economic criteria, and the influence of social factors is minimal. For systemic or network technologies – like the energy or telecom infrastructure – this simple price/performance benchmarks are insufficient (Barnett 1990). The interdependence of simultaneous changes in the system – e.g. car technology ICV vs FCV – and the related problem of refueling, hence distribution and transport of fuels requires an analysis of multiple trade-offs, for multiple components, and interfaces by multiple actors. Search, rough evaluation on the basis of asymmetric information trespass the decision making process and leave the decision makers with an enormous amount of uncertainty. In this conjuncture of contingencies social factors, like expertise of third parties, reputation of partners, and the influence of the world of finance enters the decision space to push aside these factors or rationalize them in such a way that they become conceivable.

Our case: fuel cell vehicles, fuels, and the energy infrastructure
In this section we introduce both our case and a set of factors affecting the transition trajectory we are studying. First of all we identify a set of factors related to the implementation and handling of three alternative fuels. Then we explore which of the three options is best in theoretical terms of the well-to-wheel perspective. Next an analysis is made of a set of process factors determining the transition process.

The development process of FCV's focuses mainly on three types of vehicles: FCV's fueled with hydrogen, methanol or conventional fuels like gasoline (Ogden, Steinbugler et al. 1999; Godfroij 2002).
To understand the implications of the fuel choice for the transition to a FCV based transportation system we take into account car technology, infrastructure, and environmental performance. Hence we explore the transition of systemic technology.

In order to compare the three FCV on theoretical grounds we discern two dimensions indicating the relative complexity of the transition and the relative advantages of the three technologies . The main relative advantage of the FCV's is their superior environmental performance. As one can see in Table 1 the three FCV's differ in terms of environmental performance based on the fuel efficiency of the whole fuel chain from oil drilling (well) to the end use in the car (wheel).

Table 1: comparison of well to wheel efficiency of the three fuel types (Ogden et al. 1999)

fuel type	number of cars that can be fueled with equal primary energy input
hydrogen	100
gasoline	82
methanol	57

Following our co-evolutionary perspective of technology and organization we distinguish technical and organizational complexity to describe the changes that are needed in the innovation trajectory of these FCV's. If technical networks or systems change both dimensions alter in tandem. New components in a system imply deliveries by new suppliers, hence adapted technical networks imply the entry of new stakeholders and the associated coordination efforts.

The scale of technical complexity ranges from incremental to radical change. Incremental innovations can be regarded as refinements of previous technology (Rogers 1995)whereas radical changes imply changes that dramatically divert from the existing technical function and quality of a system (wheelwright and Clark 1992). Radical

innovations may be recognized by a new set of engineering and scientific principles and may create new businesses or transform existing ones by delivering dramatically better product performance or lower production costs.
Organizational complexity can amongst other things be considered as the amount of network change – new partners e.g. suppliers, new customers - necessary to utilize the advantages and implement an innovation. The scale of network change ranges from modular to system change. This distinction is an important addition to the classification in incremental and radical innovations since it explains why even minor innovations sometimes do have a large effect on the ability of established firms to follow the innovation pattern (Henderson and Clark 1990). A modular innovation does not result in change in networks, the linkages between players remain unchanged. Technically, the changes still might be radical. A system innovation has a larger impact on the network change. It integrates multiple interdependent innovations produced by multiple actors that gradually evolve during the transitions to stakeholders . These stakeholders are mutually dependent and must collaborate to perform new functions or improve the facility performance as a whole; it involves many simultaneous changes . Many actor groups are involved in a system innovation. The organizational complexity is so important due to the fact that excellent technical solutions can become obsolete due to coalition formation between important partners in the network.

Hydrogen, when used as a fuel for a FCV, can be fed directly to the fuel cell and no complicated steps are necessary to create hydrogen on board of the vehicle. In terms of car technology, this is the simplest process. In terms of environmental performance, hydrogen performs well due to the absence of harmful emissions produced by the vehicle (hydrogen is converted into water vapor). Furthermore, model results indicate that from a well to wheel point of view hydrogen is the most efficient fuel (Ogden, Steinbugler et al. 1999)(see table 1). However, in terms of infrastructure, the use of hydrogen is complicated due to the introduction of a new fuel, that is gaseous under normal circumstances, that needs to be compressed heavily when used, and therefore has specific handling characteristics.

The interest in gasoline is based on the fact that the current fuel-infrastructure can be maintained to fuel the FCV's. A disadvantage of this technology is the complex design of the FCV since much technology is needed to convert gasoline into hydrogen. When gasoline is used in a FCV, the environmental performance is much better than for internal combustion vehicles but still harmful emissions are emitted from the vehicle.
The interest in methanol is based on the fact that methanol can be produced from biomass and on the low carbon / energy ratio of methanol. In terms of environmental performance, methanol could be a very suitable fuel, when produced from renewable resources. Well to wheel models show that when fossil fuels are used to produce methanol, the efficiency of the methanol FCV is the least efficient of the three options (Ogden, Steinbugler et al. 1999). Just like gasoline, the fueling of methanol requires a complex fuel conversion unit in the car in order to produce hydrogen. The adaptations in infrastructure are much smaller than for hydrogen since methanol is a liquid that can be handled in the same way as gasoline. However, much work needs to be done to create an extra fuelling system next to the current fuel systems that are used by cars.

Figure 1 summarizes earlier information by ordering the three FCV's in terms of technical and organizational complexity.

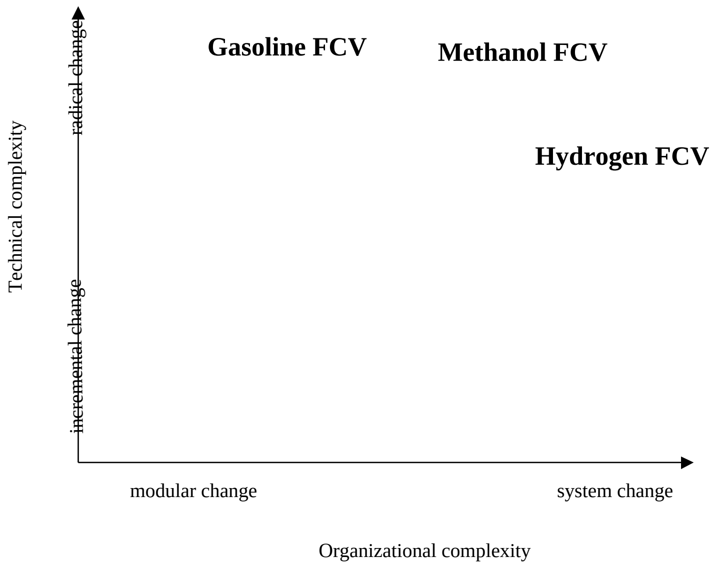

Figure 1: positioning of three FCV' sin term of technical and organizational complexity.

It shows that in terms of organizational complexity the hydrogen FCV is considered as most complex and the gasoline FCV as least complex. This is due to the necessary change in the fuel infrastructure which is large for hydrogen (gaseous fuel, handling of pressurized gas, new fueling equipment, new trucks, new pipelines, different know how) and small for gasoline FCV's (no change in fuel infrastructure). For methanol also a new infrastructure needs to be developed but due to the fact that methanol is a liquid, the infrastructure strongly resembles the current fuel infrastructure. Next to the infrastructure aspects, introduction of any FCV will require changes in know how of vehicle technology in repair facilities and users will experience different driving characteristics.
In terms of technological complexity we rate the gasoline and methanol FCV's as most complex due to the onboard reforming of the fuels. All three vehicle types are ofcourse complex in terms of new electric drive trains. The onboard storage of hydrogen is also different from traditional technology but is considered less complex than onboard reforming.

The research problem

Looking at Tabel 1 and Figure 1 it seems that the different transition routes to FCV's differ in their scores with respect to well to wheel efficiency, organizational and technical complexity. Based on this 'top down' analysis where homogeneity in actor preferences is assumes, no obvious winner can be pinpointed.
In proposition 2.1 and 2.2, and 2.3 we explicated that the choice that is at stake will be more likely if interests of actors in the actor set converge, and convergence of interests was considered a function of converging preferences, which on their turn were leveled out by the complementarities, overlap in skills and R&D of stakeholders. If all these

conditions are satisfied than we talk about the existence of a 'technological community' that pulls and pushes the transition

The research behind this paper tries to unravel the pattern of co-evolution of FCV – technologies and the network of stakeholders and asks:

1) how far the formation of a hydrogen community has come in 2001?
2) to what extent this community is able at this stage to facilitate the transition process?

To answer these questions we mapped the actors involved in the transition toward FCV's. We have asked them to what extent they collaborated (community 1), and to what extent there R&D showed some convergence (community 2), to what extent their preferences for the available fuel options converged.

3. Method

The method used consists of several steps.

1. analysis and selection of stakeholders in the development and adoption of FCV's.

Important stakeholders in the development of FCV's are car manufacturers, fuel cell producers and oil companies (Godfroij 2002). Gas stations keepers are important in the distribution of fuels. Hydrogen producers are important for technical know-how on transporting and handling of hydrogen. Early adopters of FCV's are likely to be companies that have a private fuelling infrastructure like taxi and bus companies. In this case, no investments have to be made in a complete fuelling infrastructure to try-out FCV's. Policy makers are relevant since they have an important role in the organizational process to realize a new energy-infrastructure. The final consumer / buyer is extremely important in the final decision for a certain type of FCV. In this paper all actor groups described above, except the final consumers, are taken into account. The final consumers were not included due to the completely different research method that is necessary to measure their preferences.

2. Interviews with stakeholders based on innovation characteristics

Separate interviews were prepared for each actor group. The actors were asked to score their perception of specific characteristics of the technologies and to indicate their most preferred technology. The characteristics of the technologies were based on the so called innovation characteristics as developed by Rogers (1995) (Rogers 1995). Rogers (1995) discerns several characteristics of technologies that influence the success of adoption. These characteristics are complexity, compatibility, relative advantages, observability and trialability (Rogers 1995). For every actor group these characteristics are specified regarding the assumed relation between actor and FCV technology. For example, complexity for fuel cell producers was assumed to be related to construction complexity of fuel cells while complexity for gas stations was assumed to be related to the difficulty of handling hydrogen. Table 2 shows the number of respondents for each stakeholder.

Table 2 The number of respondents per stakeholder

Stakeholder	Number of respondents	Researchers
Dutch Government	5	Van der Kuip &Meijer
Researchers of Car Industry	7	Minkman, Beffers & Schuurhuizen
Owners Gas Stations	6	De Mos & Boon
Oil Companies	6	Ros & Van Giessel
Fuell Cell Producers	7	Jorritsma & Van der Heide
Bus Companies/Manufacturers	10	Muntslag & De Boer
Hydrogen Producers	5	Oyen & De Reus
Total Sample	46	

In general the willingness to fill out the questionnaires was positive. Due to time constraints we lack data of the car industry. The email survey we developed was not filled out within the planned time, so we had to drop that part and rely on a sample of mainly researchers that are active within the field of engine technology and car manufacturing. The questionnaires were sent out in September and October 2001.

3. Patent Analysis

To gain insight in the current strategies of car manufacturers a patent analysis was done for the American market. Patent data were obtained from the US Patent and Trademark Office. The literature and patent analysis were used to create insight in the current direction of low emission technology development.
The quantity ‘entropy’ to measure the distribution of attention of manufacturers for the three types of FCV’s: hydrogen based, methanol based, and gasoline based FCV’s. Formula 1 states the mathematic expression of entropy calculation.

$$S(x) = -\sum_{x=1}^{N} p_x \cdot \ln(p_x) \qquad (1)$$

Where p_x is the number of patents for technology x divided by the total number of patents for all three technologies. When all attention is focused on one technology, the entropy has the minimum number 0. When the attention for all three technologies is evenly spread, the entropy reaches the maximum value of ln(3) = 1.1. When 5 technologies compete, the maximum entropy is ln(5) = 1.6.

4. Results

4.1 Community formation?

To make a transition feasible, stakeholders have to collaborate as is known from the network literature (Meeus, Oerlemans and Hage 2001a/b). Therefore it is important to 'know' the network intensity related to the three trajectories. We analyzed both the general pattern of collaboration, and the reasons for collaboration. We finish with the intensity of the collaboration in specific transition trajectories.

Table 3 shows the intensity of the collaboration between stakeholders. The table shows that the network is rather loose. Only the oil companies report relationships with almost all distinct partners. Fuel cell producers and hydrogen producers turned out to be rather isolated and obviously concentrate on their key accounts. Also the Dutch government concentrates its network on the oil companies and fundamental research. From (Godfroij 2002) we have learnt that car manufacturers seem to cooperate in a large network with other car manufacturers, oil companies, fuel cell producers and potential adopters like bus companies.

Table 3 Patterns of collaboration in the set of hydrogen stakeholders in terms of partner types: Oil Companies (Ros en Van Giessel 2001), Fuel Cell Producers (Jorritsma & Van der Heide 2001), Researchers Car Industry (Minkman, Beffers, Schuurhuizen 2001); Hydrogen Producers (Van Oyen & De Reus 2001), Dutch Government (Meijer & Van der Kuip 2001)

	Oil Companies	Fuel Cell Producers (Markets)	Researchers of Car Industry *	Hydrogen Producers	Dutch Government*
Fuel Cell Producers	100%	n.a.	n.a.		40%
Oil Companies	80%	n.a.	85.7%		60%
Fundamental Research	80%	n.a.	71.4%		60%
Car Producers/Drivers	100%	66.7%	100%	100%*	20%

n.a. = not analysed
* = here we asked the extent into which external actors affected the decision to participate in the transition to hydrogen
* = here we asked whether the Hydrogen Producers were able to organize Pilot Project with Car Producers
* = here we asked to report contact intensity on a 4-point scale 1 = no contact, 2 = little contact, 3 regular contact, 4 often contact. We report % > 2.

Table 4 shows in which potential transition trajectory most collaboration takes place for oil companies, fuel cell producers and the Dutch government. The patterns of collaboration seem to be most intensive in the field of methanol reforming, whereas policy initiatives are almost absent. This is slightly at odds with our expectations that oil companies would do most work on the gasoline transition since this relates to the core of their vested interests and that fuel cell producers work most on the direct hydrogen since this is technically the optimal fuel for fuel cells. The focus on methanol in the collaboration activities of both parties may be explained by the argument that oil companies do not want to share knowledge in their main competence area's and that fuel cell producers develop partnerships in other routes than hydrogen in a search for complementary competences. The difference in strategy may be explained that the vested interests in the current infrastructure are high for oil companies and almost zero for fuel cell producers. The Dutch government is not yet strongly involved in policy initiatives to induce or support collaboration.

Table 4 Patterns of collaboration in the set of hydrogen stakeholders in terms of ranked average number of partners (Ros & Van Giessel 2001), Fuel Cell Producers (Jorritsma & Van der Heide 2001), and the Dutch Government (Meijer & Van der Kuip 2001: 28)

Type of fuel/fuel cell/reformer	Oil Companies	Fuel cell producers	Dutch Government*
Direct hydrogen	3 (1.0)	2 (1.2)	1 (1.2)
Methanol reforming	1 (1.7)	1 (1.7)	2 / 3 (1.0)
Gasoline reforming	2 (1.2)	3 (0.0)	2 / 3 (1.0)

* here we asked about policy initiatives inducing collaboration within the transition trajectories. 1 = no measures 5 = high policy intensity.

Table 5 shows the motives for collaboration. The table shows that still many motives for collaboration play a role. This indicates that the whole trajectory is in its earliest phase.

Table 5 Reasons for cooperation in the set of hydrogen stakeholders in terms of partner types: Oil Companies (Ros en Van Giessel 2001), Researchers Car Industry (Minkman, Beffers, Schuurhuizen 2001).

	Oil Companies	Researchers of Auto Industry
Knowledge Acquisition	80%	71.4%
Market Positioning	100%	42.7%
Cost Reduction	100%	71.4%*
Pilot Projects	80%	n.a.
Creating a technology standard	n.a.	71.4%

* here we report sharing of research costs, sharing of production costs was considered equal to or more than important only 14.3%.

4.2 Converging interests?

Several indicators were used to measure convergence in interest. First of all a ranking was made of preferences for the alternative transition trajectories. Next we looked at the distribution of R&D activities on the three transition trajectories, and we took into account outcomes of R&D activities of the fuels. Furthermore we ranked transport / distribution options of hydrogen.

Converging preferences of other stakeholders regarding transition routes

We consider the transition to large scale implementation of FCV's as a form of collective action of a set of heterogeneous actors. As said before one of the important aspects of successful transitions is that actors involved in the transition become stakeholders that intentionally cooperate to achieve positive externalities and economies of scale and scope with a shared mission. The question is to what extent this alignment of interests has already taken place or whether there are only some indications at this very moment.

Table 6 shows that our sample of actors in the transition at stake have converging preference as to three transition trajectories in this paper. Fuel cell vehicles fueled directly with hydrogen seems to be the most preferred option. This is a remarkable finding in the sense that exactly this option requires the most drastic infrastructural adaptations and probably is the most complex trajectory from an organizational point of view.

Table 6 Ranking of preference for transition options of the Dutch Government (Meijer & Van der Kuip 2001, 17), Fuel Cell Producers (Jorritsma & Van der Heide, 2001), Bus Companies/Producers (Muntslag & De Boer 2001), Research Car Industry (Minkman, Beffers, Schuurhuizen 2001), and Oil Companies (Ros & Van Giessel (2001)

	Dutch Government	Fuel Cell Producers	Research Car Industry	Bus Companies/Manufacturers	Oil Companies
Compressed gas hydrogen storage	1 (4.0)	1 (2. 8)	1 (58%)	1 (66.7%)	1 / 2 (2.0)
Steam Reforming of Methanol (SMR)	3 (0.5)	3 (1.6)	2 / 3 (14%)	2 (33.3%)	3 (1.2)
Partial oxidation of hydrocarbons (POX)	2 (1.3)	2 (1.7)	2 / 3 (14%)	3 (0%)	1 / 2 (2.0)

Please note.
% were used to rank preferred transition options if question was: Choose the most preferred option, and the three transition options were answering categories.
Average scores were used to rank preferred transition options if respondents were asked to rank the transition options from most (rank 1) to least preferred (rank 3) option.

Convergence of preferences of stakeholders regarding design of hydrogen infrastructure

As said before, it is remarkable that all actors seem to prefer the transition route based on hydrogen as fuel. Hardly any experience of using hydrogen in the transport sector has been gained so far. When using hydrogen as a fuel several alternatives are described in literature for production and transport. The first option is to produce hydrogen in a large facility and transport it by means of a pipeline to gas stations. Another option is to transport the centrally produced hydrogen as a compressed gas by truck. Finally, it is also possible to produce hydrogen on site (by either electrolysis of water or reforming of natural gas) (Ogden 1999).

To achieve the implementation of a hydrogen infrastructure it is important to develop a shared conception of a system of fuel production, distribution and handling at the gas stations. Table 7 states the preferences of a number of stakeholders regarding the most preferred infrastructure. The table shows that there is less convergence than with the transition trajectories. Central production of hydrogen and distribution and transportation by means of pipeline systems is the most preferred option of 3 out of 4 stakeholders, whereas the most involved actors – owners of gas stations and oil companies – diverge.

It becomes clear that the oil companies pursue to preserve their market position, which is based on central production and a large truck based distribution system. This part of their business activities would be threatened by a pipeline system, or in case they would want to take the lead this option would imply enormous investments on their part to maintain their market position. In the same way, gas station owners prefer an option that at first sight gives them more room for maneuver, namely a production facility located at the gas station. This makes them less dependent of the oil companies.
It is remarkable that gas station owners do not radically reject the option of becoming a hydrogen producer. It can be expected that a large knowledge gap needs to be filled before a gas station owner can become a hydrogen producer that is running a small chemical factory.

Table 7 Ranking of preferred Transport / Distribution options of hydrogen according to Gas Station Owners (De Mos & Boon, 2001), Oil Companies (Ros & Van Giessel 2001), Hydrogen Producers (Oijen & De Reus, 2001), Bus Companies/Manufacturers (Muntslag & De Boer 2001)

Configuration of Fuel, Production and Transport	Gas Station Owners	Oil Companies	Hydrogen Producers	Bus Companies/Manufacturers*
Hydrogen produced in a centralised reforming plant and delivered by a hydrogen gas pipeline	1 / 2 (3.3)	2 (1.5)	1 (2.8)	1 (33.3%)
Hydrogen is produced in a centralised reforming plant and compressed truck delivered	3 (2.2)	1 (1.8)	2 (2.0)	2 / 3 (16.7%)
Hydrogen is produced at the refuelling station and pipeline delivers the gas	1 / 2 (3.3)	n.a.	n.a.	2 / 3 (16.7)

Note.
n.a = not analysed
* or the Bus Companies/Manufacturers 2 of the respondents misunderstood the question and ticked more than one option, therefore the percentages reported do not add up to 100%.

Results of patent analysis

In (Godfroij 2002)1078 patents were found that deal with clean propulsion technologies for cars. 743 patents dealt with fuel technologies. The bulk of these patents (67%) were patented by car manufacturers, some were patented by oil companies (9%) and specialized technology developers (24%).
Figures 1 and 2 show the number of patents for different fuel technologies in the period 1980 – 1990 and 1990 – 2000 respectively. Note the different scales on the y-axis.

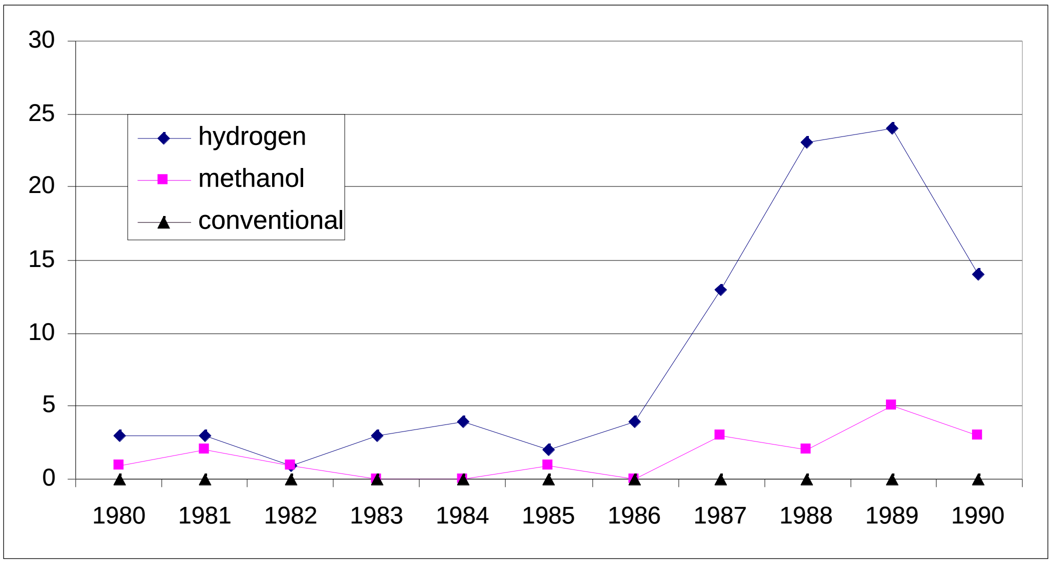

Figure 2: the number of patents per fuel technology for the different fuels for the period 1980-1990.

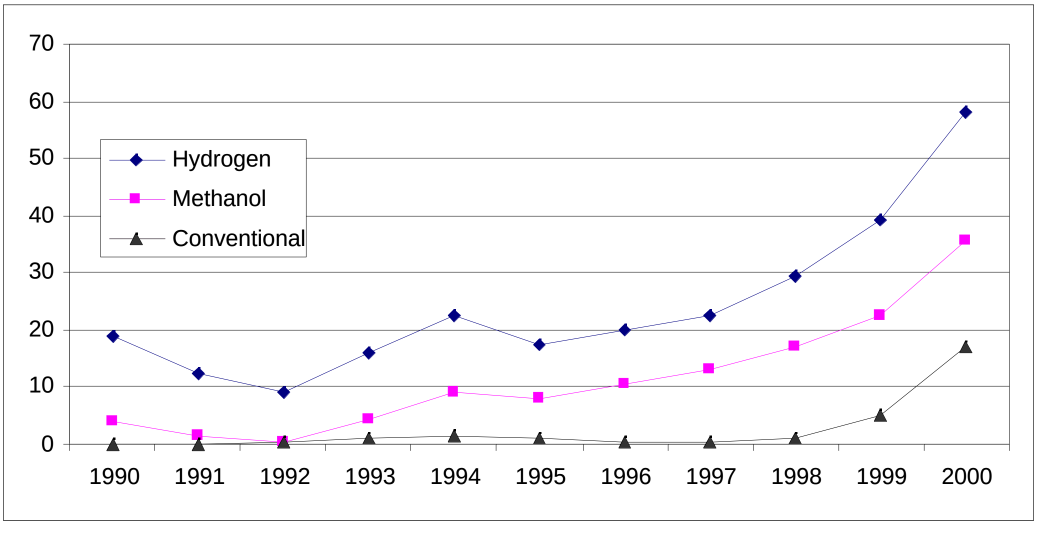

Figure 3: the number of patents per fuel technology for the different fuels for the period 1990-2000.

Figures 2 and 3 show that much more patents are registered after in the period 1990 – 2000 than in the period 1980 – 1990. It might not be a coincidence that the zero emission vehicle mandate of the state California was signed in 1990. The figures also show that most patents are focused on hydrogen as fuel, followed by methanol. Furthermore, attention for the conventional fuels strongly increases in the last few years.

When we look at the entropy of attention distribution for the development of FCV's running on different fuels in the period 1990 – 2000, it becomes visible that the beginning

of the period is already characterized by a high entropy level and that this level is increasing in the next decade (see figure 4). Thus a distinct trend towards more diversification is visible. In 1990 the attention was mostly focused on using hydrogen as fuel, in 2000 most attention was still directed at using hydrogen but also much patents were patented about methanol technology and conventional fuel technology.
Based on this patent analysis we can conclude that no choice has been made by the car producers for a specific fuel for fuel cell vehicles. The development process still seems to be in the diversification stage.

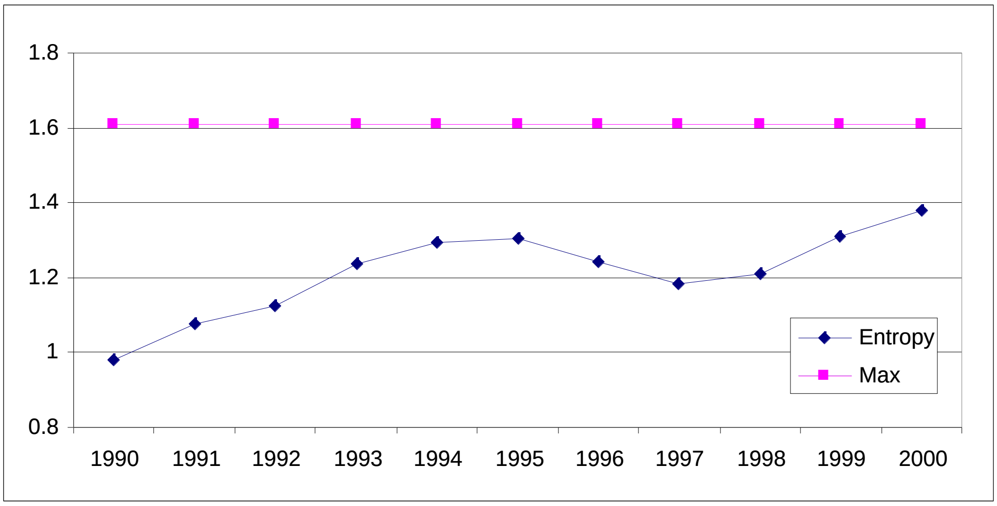

Figure 4: Entropy of attention distribution for different fuel technologies for FCV's in the period 1990 - 2000

Convergence of R&D expenditures on the three transition routes

Because the technology is still in a developmental phase lots of R&D needs to be done on fuel cells, reformers, safety of the onboard technologies like fuel tanks, infrastructure, etcetera. Therefore, another important condition for the feasibility of transitions requiring innovations that are both technically and organizationally complex is that there is also a certain interest in R&D investment. Table xx ranks the R&D expenditures of several stakeholders. The results indicate a good fit between the R&D expenditure of the stakeholders and their position in the network. The fuel cell producers invest the most research activities in the direct hydrogen fuel cell. From their point of view this is a logical move since hydrogen is technically the most feasible fuel for fuel cells. Oil companies on the other hand have interest in maintaining the current fuel infrastructure and invest in gasoline powered FCV's. Based on the patent analysis we know that most research efforts of the car manufacturers is dedicated to hydrogen fuel cells but that the other options also receive much attention, with a strong growth of attention for conventional fuels in the last years. Obviously, car manufacturers are optimizing on both the technical complexity as on the organizational compatibility of the new technology.
It is remarkable that the Dutch government is most willing to invest in the gasoline powered FCV's. Obviously, the government feels uncomfortable with the large

organizational changes that are necessary for a hydrogen infrastructure. They prefer modular network changes. It is also remarkable that from Table xx we learnt that the Dutch government prefer the transition trajectory based on hydrogen the most but are not willing to invest the most in this option. A possible explanation is that the government may not realize the fact that hydrogen seems to be the most preferred option for many stakeholders.

Tabel 8 Ranking of importance of transition trajectories in terms of size of R&D investment by Fuel Cell Producers (Jorritsma & Van der Heide, 2001: 21), the Dutch Government (Meijer & Van der Kuip 2001, 17), Reserachers of the Car Industry (Minkman, Beffers, Schuurhuizen 2001), and Oil Companies (Ros & Van Giessel 2001).

Type of fuel/fuel cell	Relative amount of R&D investment of **fuel cell producers** in type of fuel cells	Relative willingness to stimulate R&D by **Dutch Government**	Relative amount R&D investment of **Oil Companies** in fuel types	Patent frequency of care manufacturers in type of FCV's
Direct hydrogen	1 (5.1)	3 (6.7)	2 (4.0)	1
Methanol reforming	2 (3.7)	2 (7.0)	3 (3.0)	2
Gasoline reforming	3 (3.6)	1 (7.3)	1 (4.5)	3

5. Discussion and Conclusions

As to research question 1 we conclude that there is an emergent network of stakeholders. Our data suggest that the network seems to be dominated by car manufacturers and the oil companies. This finding is important for two reasons. First, because this implies that these actors will probably initiate the formation of coalitions in the actor set, which is a threshold for technologies that were not developed by themselves or in their alliances. Second, because of the dominance of these actors the alignment of interest will be enforced by them, the likelihood of initiatives of the less central players will be hampered. Furthermore the central role of two global players in this network enlarges the likelihood of delay if technical developments are to threatening for their core businesses. For the short term the core businesses that remains are gasoline production and distribution and ICEV's, so hold up strategies are very likely, without strong international regulatory pressures.

Our results as to research question 2 regard the extent into which the network has converging R&D activities, converging preferences for the fuel options and converging preferences for the design of the infrastructure.
Although car manufacturers have not made the final choice for a transition trajectory towards FCV's based on hydrogen, methanol or gasoline, it becomes clear from the patent production that most patents are related to the use of hydrogen as a fuel. This is technically the least radical technology but requires large organizational changes in the infrastructure (system innovation). The R&D activities of the other stakeholders do not reveal a pattern.

This scattered pattern of R&D priorities might reflect on the one hand competition between the old R&D trajectories with the R&D in direct hydrogen, and on the other hand the fact that companies are still in a very early stage. Yet, the patenting frequency in the field of hydrogen however guides the attention for sure and will make the innovation race converge toward the new fuel options. Another option is that oil companies as well as car manufacturers strive for strong performance improvements in terms of energy efficiency of their existing products.

Despite this lack of convergence in R&D activities stakeholders seem to agree fully with respect to the best transition option. They rank compressed gas hydrogen storage as the most preferred transition option. This convergence is less strong with respect to preferred transport and distribution options, but nevertheless strong enough to know that there might be a bottleneck here. The oil companies are strictly speaking the ‘outlier’ here. Obviously they are perfectly aware of the strategic impacts of pipeline transport.

In sum our findings show convergence in preferences for transition routes, but the R&D activities as well as the preference for the design of the transport / distribution infrastructure reveal that the ‘community’ consists of players with substantially different business interests.
Conditions for the transition seem to develop but predominantly in terms of the development of a knowledge base (patent pool). As to the transition trajectory itself this implies that international regulatory pressures will probably be necessary to push the whole process further.
Only the patent data that gives information about the research activities of car manufacturers and car component producers has reasonable quality. The questionnaire data have to be interpreted with the greatest care. Therefore, the results of this study should be regarded as exploratory findings that need to be verified in much more detailed matter. Currently, Utrecht University is working on this subject.

References

Barnett, W. P. (1990). "The Organizational Ecology of a Technological System." Administrative Science Quarterly **35**(1): 31-60.
Godfroij, P. (2002). The transition route to low emission vehicles. Utrecht, Utrecht University, department of Innovation Studies**:** 100.
Henderson, R. M. and K. B. Clark (1990). "Architectural Innovation: the reconfiguration of existing product technologies and the failure of established firms." Administrative Science Quarterly **35**: 9-30.
Houghton, J. T., et al. (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
Jorritsma, S. and H. van der Heide (2001), Transition to FCV, a fuel cell producer perspective, Utrecht University, department of Innovation Studies, internal report
Lente, H. v. and A. Rip (1998). "The rise of membrane technology: From rhetorics to social reality." Social Studies of Science **28**(2): 221-254.

Meeus, M.T.H., Oerlemans, L.A.G., Hage, J., 2001, *Patterns of Interactive Learning in a High Tech Region. An empirical exploration of an extended resource-based model. Organisation Studies,* Vol. 22. No. 1, pp. 145-172.

Metz, B., O. Davidson, et al. (2001). Climate Change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

Meijer, I. and M. van der Kuip (2001), Transition to FCV, a government perspective, Utrecht University, department of Innovation Studies, internal report

Minkman, S. T. Beffers, and R. Schuurhuizen (2001), Transition to FCV, a car industry perspective, Utrecht University, department of Innovation Studies, internal report

Moore, G. M. and G. Banbasat (1991). "Development of an Instrument to Measure the Perceptions of Adopting and Information Technology Innovation." Information Systems Research **2**(3): 192-222.

Muntslag A. and S. De Boer (2001), Transition to FCV, a bus company perspective, Utrecht University, department of Innovation Studies, internal report

Ogden, J. M. (1999). "Prospects for building a hydrogen infrastructure." Ann. Rev. Energy Environ. **24**: 227-79.

Ogden, J. M., M. M. Steinbugler, et al. (1999). "A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development." Journal of Power Sources **79**(2): 143-168.

Podolny, Joel M., 1993, A status-based model of market competition. *American Journal of Sociology* 98: 829-872.

Podolny, Joel M., and Toby E. Stuart, 1995, A role-based ecology of technological change. *American Journal of Sociology*, 100: 1224-1260.

Reus, S. de and J. van Oijen, (2001) Transition to FCV, a hydrogen producer perspective, Utrecht University, department of Innovation Studies, internal report

Rogers, E. M. (1995). Diffusion of innovations, 4th edition. New York, Free Press.

Rosenkopf, Lori, and Michael L. Tushman, 1994, The coevolution of technology and organization. In Joel A.C. Baum, Jitendra V. Singh (eds.), *Evolutionary dynamics of organizations.* Oxford University Press: Oxford. Pp. 403-425

Ros, M. and J. van Giessel (2001) Transition to FCV, an oil company perspective, Utrecht University, department of Innovation Studies, internal report

organization. In Joel A.C. Baum, Jitendra V. Singh (eds.), *Evolutionary dynamics of organizations.* Oxford University Press: Oxford. Pp. 403-425

Tornatzky, L. G. and K. J. Klein (1982). "Innovation Characteristics and Innovation Adoption-Implementation: A meta-analysis of findings." IEEE Transactions on Engineering Management **29**(1): 28-45.

Wheelwright, S. C. and K. Clark (1992). Revolutionizing Product Development. New York, USA, Free Press.