Competing Expectations
The case of the hydrogen car

Funding for this research project was provided by the Advanced Chemical Technologies for Sustainability (ACTS) programme of the Netherlands Organisation for Scientific Research (NWO). Additional support for printing costs is provided by the Onderzoeksschool voor Wetenschap, Technologie en Moderne Cultuur (WTMC).

ISBN 978-90-8891-258-0

Printed by: Proefschriftmaken.nl || Printyourthesis.com
Published by: Uitgeverij BOXPress, Oisterwijk

Competing Expectations
The case of the hydrogen car

Concurrerende Verwachtingen - De casus van de waterstofauto

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht
op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen

op vrijdag 15 april 2011 des ochtends te 10.30 uur

door

Sjoerd Bakker

geboren op 19 april 1977 te Amsterdam

Promotoren:

Prof.dr. ir. H. van Lente

Prof.dr. E. Worrell

Contents

1. Introduction

Firms and governments can support only a limited number of emerging technologies. Some emerging technologies receive support for further development while others are discarded. But how do decision makers in firms and governments assess which of the options earns their support? Straightforward assessments of prices and performance levels can not be sufficient as emerging technologies are, by definition, in an early stage of development and have not reached their maximum levels of performance yet. It is therefore not so much of interest which of the options performs best at any point in time, but rather which of the options will eventually perform best in the future.
In this thesis it is questioned how emerging technologies compete and how both the relevant decision makers and the technology developers deal with expectations of technological feasibility and future price and performance levels of the different options. It is studied how technology developers use expectations of their options and how the decision makers assess the credibility of those expectations.

The analysis in this thesis revolves around the development of hydrogen powered cars. The hydrogen car challenges the design of the car as we know it. The current design, a gasoline-powered internal combustion engine, is under pressure from different sides. Because of inevitable shortage of supplies, oil prices will rise and geopolitical issues will become more pressing. And furthermore, concerns about climate change and local air pollution are expected to trigger more stringent emissions regulations. Together, these pressures shape a need for 'the car of the future' which is imagined to be independent of fossil fuels and free of harmful emissions. The prospect of the end of the car as we know it triggers a double-edged response from the car industry. On the one hand, the car industry is reluctant to give up its core design. But on the other hand, the industry is also engaged with developing different options for the car of the future. The notion of the car of the future thus provokes a competition between different options that are proposed by firms and other technology developers. The hydrogen car is one of the main contenders to substitute today's cars, but it faces competition from other radical alternatives like

battery-electric and plug-in hybrid vehicles and also from incremental innovations such as biofuels and natural gas powered cars. In such a competition, in which all options are surrounded with much uncertainty, the question is thus which of the options is the most promising? Not only is there much uncertainty with regard to technological feasibility of the different options, the notion of the car of the future might also change over time and be subject to debate.
And, making matters more complex, there is not only an ongoing competition between these different 'cars of the future', there is also competition between different designs of the hydrogen car. In forty years of development, for example, many different technological options have been applied to store the hydrogen on-board the cars and to convert it to power. And here the same question applies: which of the options is the most promising?

In this thesis, the competition between emerging technologies is studied at both levels: at the *system* level of the 'car of the future' and at the *component* level of the different hydrogen storage and conversion technologies. It is questioned how expectations of the options were raised and used by their developers and why these expectations were thought to be credible and others were not. Conceptually, the competition between the emerging technologies is studied through a quasi-evolutionary model of technological innovation to make the role of technological expectations explicit.

Expectations and the hydrogen car

Emerging technologies compete for funding for further development, other forms of support such as governmental regulations and perhaps even for adoption by consumers in early niche markets. Given their early stage of development, the competition cannot simply be about technological performance and costs. Rather than about factual criteria, the competition is about claims of potential future performance levels and future selection criteria. In other words, the different cars of the future do not compete on the basis of what they can do, but rather on the basis of what they are expected to do in the future.
In terms of innovation studies, the goal is to study the role of expectations in pre-market competition between emerging technologies and, more specifically, the question of how expectations are used, shared, and assessed by different actors. The goal is also to acquire an understanding of the dynamics of the development trajectory of both the car and its enabling technologies. The use of hydrogen as a car fuel has always been subject of fierce debates and it has seen multiple ups and downs in terms of attention and expectations. To some of its supporters, the hydrogen car is the panacea to all conceivable energy and transport problems. To its opponents it is inefficient, too expensive, and too complex. Clearly, expectations play a significant role and one of the goals of this project is to measure expectations and to study how they enable and constrain the development of hydrogen options, in particular in the case of dynamics of hype and subsequent disappointment. A technological option may be supported on the basis of high expectations, but in the case of inflated expectations, an instance of hype, disappointment is looming and such disappointment may cause actors to withdraw their support. A better understanding of such dynamics might be of help to some form of expectations

management in order to smooth out the highs and lows in an innovation trajectory and end up with a steadier and more predictable trajectory with less societal costs.

1.1 Innovation theory on competing technologies

The hydrogen car is proposed as an alternative to the internal combustion engine car. Here, the well established technology is challenged by a new option: a case of *old versus new* competition. At the same time, the hydrogen car is not the only alternative and a multitude of cars of the future compete with one another to become the eventual challenger of the gasoline car. And, as was described in the introductory chapter, there are multiple design options for the hydrogen car as well. Between the emerging technologies, *new versus new* competition takes place. How can such a competition be analyzed and understood? To develop a theoretical framework for such an analysis, a short overview is provided of the relevant innovation studies literature. And building on these insights, the research question is discussed. Finally, the selection of specific hydrogen-related case studies and research methodologies are introduced.

Innovation as an evolutionary process

Technological competition is a prominent subject in innovation studies. But in a field as broad as innovation studies, it is no wonder that different perspectives are applied to this subject. A major distinction is found between the economists' perspective and the social-constructivists' perspective.

The economists' perspective is most concerned with innovation as a factor in economic development. That is, innovation is pursued by economic agents who seek to improve products and processes and the interest is with the impacts of their activities on the growth of individual firms, industries, and economies. A particularly interesting and valuable strand in economics, with regard to innovation, is found with so-called evolutionary economists (Dosi and Nelson 1994, Nelson and Winter 1982, Kemp and Soete 1992). Whereas (neo-) classical economists treat actors as all-knowing and fully rational, the evolutionary economists accept that actors are limited in terms of what they (can) know and decide upon. The bounded rationality of actors makes that different actors make different assessments and that they will develop different solutions to problems. Or, framed positively, they develop different ways of seizing an opportunity.

Such bounded rationality results in different technological options that are offered by different actors (van den Bergh et al 2006). These options are the variations in an evolutionary model of variation, selection, and retention. From the variety of technological options, a selection is made in the relevant selection environment (i.e. the market). Those options that are positively selected survive on the market and can be considered to be successful innovations. Over time, a successful option is repeatedly selected and this option and its selection environment will adopt more and more to each other. Eventually, this retention gives rise to a (socio-) technical regime that is shaped by a dominant technology and everything that surrounds it in terms of infrastructure, regulation, maintenance networks, etc. For any alternative option it will be, as a consequence, even more difficult to be selected in that environment.

In evolutionary economics such effects are called path-dependencies (David 1985, Arthur 1989). Most firms, and actors in the firms, agree on what works best and share the same search routines in further innovative activities. And as a result all actors innovate along the same trajectory, or evolutionary trait, of descendants. Innovation is then mostly incremental and is limited to small improvements or variations of the existing and dominant sociotechnical regime (Kemp et al 1998). And, the dominant technology also benefits from economies of scale and network externalities that any new technology would lack. This can result in a situation of technological lock-in: more radical innovation is hampered because truly different variations are effectively shut out. The *old versus new* competition is the struggle of new variations to breach this lock-in.

New versus new competition

In the case of emerging radical innovation, there is also *new versus new* competition between different options. That is, new variations are being developed to substitute the old regime and the question is which variations will end up challenging the old regime. The most straightforward perspective on technological competition is that the winning technology, or design, outperforms any other design in terms of performance and price (Abernathy and Utterback 1978, Anderson and Tushman 1990, Christensen and Rosenbloom 1995). These explanations thrive on the assumptions that both the price and the performance of the options are known and measurable. And that the actual selection criteria are the same and known to all actors. In other cases it was shown that governmental regulations may favour one of the competing options, and that strategic manoeuvring by firms may also be decisive (Murmann and Frenken 2006).

However, these explanations relate only to competition between technologies that are available on the market. In the case of emerging technologies, future price and performance levels are unknown and so are the exact selection criteria, including governmental regulation, that will eventually apply in future markets. To economists this limited scope does not seem a problem, as they are interested in the innovation process as a factor in economic development and the role innovation has in sustaining and changing (industrial) economic landscapes. The competition between different technologies is thus of interest to them in the sense that it is a competition between firms or entrepreneurs that develop and aim to commercialize the technologies.

The actual processes of discovery and development of new technologies are therefore often black-boxed by economists (Rosenberg 1982). To understand technological innovation more thoroughly one needs to take into account the pre-sorting that takes places in the pre-market stages of innovation.

A constructivist's perspective

Whereas economists focus on price and performance as unique selection criteria, sociologists of technological innovation have developed another perspective. Their proposition is that any technological option, be it a single artefact or a technological system, may have different meanings and purposes to different actors. And, as a consequence, the notion of technological performance is problematised and can no longer be understood unequivocally. This is, in short, the argument of the Social Construction of Technology (SCOT) approach (Pinch and Bijker 1984, Bijker 1995, Bijker 2010). Different actors, or actor groups, hold different ideas, and different measures of performance may apply. And, performance is not necessarily measurable and quantitative. To say that a winning technology was, in hindsight, the better performing option does not do justice to the complexity of the competition and the process of variation and selection. The outcome of the competition is the result of interactions and negotiations of different groups of stakeholders such as producers, consumers, regulators etc. And, the competition is only settled when the different groups of actors have reached closure on what the most important problems, and thus, selection criteria are and what design fits best with those criteria.

Like the evolutionary economists, the SCOT approach regards innovation as a process of variation and selection. It seeks to incorporate the notion of interpretive flexibility of technological options and to get away from the idea that there is something like an objective and unique measure for technological performance.

The question in this thesis is what happens before technologies enter the market before interactions and negotiations between the traditional demand and supply sides become effective. Others scholars have, also from a constructivists' point of view, incorporated such dynamics of pre-market competition. Rip and van de Belt, for instance, have recognized the potential of the evolutionary perspective for the understanding of technological innovation from a sociologists' perspective (van den Belt and Rip 1987). They have also recognized that there is a fundamental difference between biological variation and selection and sociotechnical variation and selection. That is, innovation is a social activity and the technological variations are produced by actors with some anticipation of future selection environments: innovating actors have some clues of what will be successful in the future.

Likewise, the selection environment is also formed by people and they are capable of anticipating future developments and changing selection criteria. Hence, there is a strong element of anticipation in both variation and selection and one can only speak of quasi-evolution in technological innovation (van den Belt and Rip 1987, Schot 1992). The anticipation in both variation and selection relates to what the involved actors expect of the emerging variations and their future selection environments. And this is where technological expectations come into play: in a '*speculative market of early promises*' and '*cultural matrix of expectations'* (van den Belt and Rip 1987) or in a '*quasi-market of technological options*' (Schaeffer 1998).

Technological expectations

Before technologies can compete on the market, they go through a long and uncertain process of research and development. During this phase, the new options are far from 'better' than the old technology, but different expectations circulate about the technologies' future potentials. The development of these options and the necessary investments are thus not so much based on actual performance, but rather on promises and expectations.

The hydrogen car is a good example as it relies on a number of enabling technologies that are currently not commercially available for automotive use. In order for the hydrogen car to be ever realized, its enabling technologies need to be developed further. One who 'believes' in the hydrogen car thus holds a 'believe' in the future potential of the enabling technologies. Such a belief in the future potential of any technology can be labelled to be 'technological expectations'. Technological expectations, ideas on what a technology is capable of in the future, have a relatively long history in innovation theory. For instance, Cyert, March, and Mill have already written about the role of expectations in business decision making in the 1950s (Cyert et al 1958). Another early source that is often referred to is Rosenberg (Rosenberg 1976), although his interpretation is somewhat different from later interpretations and certainly from the one that is used in this thesis. For Rosenberg, expectations are those convictions that technology will improve in the future and these make that consumers delay their purchases of products until a new generation is on the market or until the price has decreased. Whereas these interpretations are mostly concerned with individual expectations, Van Lente has brought a sociological interpretation of technological expectations to the attention of innovation scholars. He has done so especially to those with a constructivists' perspective in the field of science, technology, and innovation studies (STIS)[1]. Van Lente's interpretation is that expectations guide technological innovation and that they are an essential element of technology dynamics (van Lente 1993). In later years this perspective was adopted by others and was developed into what is now known as the sociology of expectations (Borup et al 2006, Brown and Michael 2003). A working definition of expectations was provided in the introductory paper of a special issue in Technology Analysis & Strategic Management: '[technological expectations are] *real-time representations of future technological situations and capabilities'* (Borup et al 2006). Technological expectations are thus not only about future capabilities, or performance levels, of a single technological option, they may also deal with societal acceptance and uptake, commercial success, the conditions to make this possible in future societies, markets, and other technologies and systems that together shape the context in which the technology is to function and is hoped to be successful.

Such expectations do not come about spontaneously: they are the product of human agency and they circulate. Some actors may voice expectations rather spontaneously, and some actors communicate expectations as part of a deliberate strategy.

Actors with a specific interest in a specific technological option might try to influence others with their statements and by doing so they attempt to '*colonize the future'* (Brown and Michael 2003). Or, along the same lines, they make a *bid* on a desirable future outcome of the innovation process (Berkhout 2006). In such cases where expectations are used deliberately and rather normatively, one can also speak of promises (Borup et al 2006).

Intentionally or not, expectations matter. They are performative in the sense that they influence innovation processes. They do so because they stimulate, steer, and coordinate actors' actions and

1 A somewhat less elaborated notion of the role of expectations was already included in the quasi-evolutionary framework of Van de Belt and Rip (1987).

decisions towards the future. In certain cases this may amount to self-fulfilling prophecies. Once people adopt a set of expectations, they will act accordingly and the expectations stand a greater chance to actually become future realities. However, in extreme cases of widely shared and high expectations, expectations can be driven to such heights that one can speak of (technological) hypes. In those cases, the high expectations are unlikely to be fulfilled, are regarded as inflated, and that, in turn, can lead to disappointment. The disappointment with a technological option may cause actors to withdraw from the development of the option and trigger the death of the prophecy: then one can speak of suicidal prophecies.

In the sociology of expectations the emphasis is on these powers of technological expectations. That is, the analysis focuses on the performativity of expectations: on what expectations can *do*. Expectations however, are only performative once they are shared by many actors. In the sociology of expectations, these expectations are called 'collective expectations'. A collective expectation is an expectation that is shared or at least known by many actors. These are then part of social repertoires: they are often and easily referred to and are not fiercely contested each time they are brought up. The sociology of expectations is indeed interested in the structuring role of expectations, much more than in the individual (psychology of) expectations. In other words, the interest is with collective expectations that help to shape prospective structures (van Lente and Rip 1998a).

With its focus on the collective and on the structuring role of expectations, the sociology of expectations may be of help in understanding how expectations have guided the search for the car of the future. Where these expectations come from and why some are thought to be credible and others not, is less addressed in this body of literature. In the next section it is argued that, to understand the competition between emerging technologies, a more thorough understanding is needed of the rise, maintenance and assessment of collective expectations and the role of agency therein.

1.2 Towards a combined model of competing emerging technologies

To summarize, there are two complementary perspectives that can be of use to this thesis: the quasi-evolutionary model of innovation and the sociology of expectations. The quasi-evolutionary model addresses the competition between technological options and it embraces the role of expectations in the innovation process. It does so however only in rather unspecific terms. The sociology of expectations has taken on the task of explicating the role of expectations in innovation processes, but has been less interested in competing expectations and can be strengthened with a more thorough understanding of the agency that is involved in the shaping and assessment of expectations. Such an elaboration is also necessary to come to terms with the diverse sets of actors that develop the competing technological variations and those actors that together shape a pre-market selection environment.

It is fruitful therefore, to combine, if not re-unite, the two perspectives to form a research framework for competing emerging technologies. An essential link is provided by Garud and Ahlstrom (1997). They argue that a socio-cognitive 'game' is played between, on the one hand, insiders that create or 'enact' technological development ('enactors' as suggested by Rip (2006)) and, on the other hand, outsiders that select technologies according to their own criteria ('selectors'). Enactors create and put forward technological variations that they claim to be solutions to perceived problems. Selectors, however, start with their (often different) perception of the problem that needs to be solved, and assess how various technologies may contribute to a solution. The criteria in such assessments however are not necessarily stable and shared by all actors, as many studies of technology have shown (Bijker 1995, Garud and Rappa 1994). As a consequence, criteria are shaped by actors' needs, vested interests, lobbying and learning processes. There is not one best technological solution to a single problem: for different actors, different technologies fit best. According to Garud and Ahlstrom, enactors and selectors meet in so-called 'bridging events' such as funding decisions or technology assessment exercises. Garud and Ahlstrom, thus provide an essential element in the conceptual framework with the actors that are involved in the competition.

In their framework, the role of expectations is rather implicit. However as the selectors cannot assess the value of the diverse technological options based on actual performance but rather on expected future potential. Their decisions are thus based on expectations, rather than on facts (Glynn 2002). On both sides, criteria are used to assess variations, both in terms of expected performance (ex-ante) as well as in terms of actual performance (ex-post). Enactors, for instance, will stress the criteria that favour their particular variation. Technology selectors, on the other hand, have to balance a number of sometimes contradicting criteria and this balance could very well shift over time. The outcomes of processes of quasi-evolution of technology are therefore as much determined by social processes, such as strategic games and the construction of needs and selection criteria, as they are by material characteristics.

Who then are the enactors and selectors? As many emerging technologies are highly complex and systemic in nature, it takes a multitude of actors and organisations to develop the actual technologies. An important conceptualization of such groups of actors and organisations is provided in the literature on technological communities (Rappa and Debackere 1992, Debackere and Rappa 1994, Lynn et al 1998, Rosenkopf and Tushman 1998). The concept of technological (or innovation (Lynn et al 1996)) communities is used to describe and understand the inter-actor and inter-organizational behaviour in innovation. The members of the community are globally dispersed but have a shared goal to develop solutions and a shared interest in convincing technology selectors of the future potential of their work. For most technologies, a technological community can be discerned. And each technological community can be expected to consist of scientists and engineers in academia, research institutes and industry.

The selectors on the other hand are more difficult to define. Often, they do not form communities like the enactors do and do not share a common interest to the same extent. Nonetheless, governments and firms do make decisions with regard to supporting, or not, emerging technologies. And because their resources are finite, they cannot support all available options and can only select the most the promising options.

Note however, that the distinction between the enactors and the selectors is ontologically not as strict as it is portrayed here. They are roles, rather than fixed positions and actors may perform the role of enactor in one context and that of selector in another. However, for analytical purposes it is worthwhile to distinguish between the two sides. Otherwise, one is left with a pool of visions and expectations and is it impossible to discern the agency that is involved in filling the pool and filtering out those expectations that are thought to be relevant and credible.

In Figure 1.1, the core of the research framework is depicted. On opposite sides are the enactors (with their technological variations) and selectors (with their selection criteria) and technological expectations function as the linchpin between the two sides. That is, the enactors try to raise expectations of their own variation and the selectors assess the credibility of the diverse variations. The option that is deemed most credible will be positively selected. A further elaboration of the framework is provided in Chapter 2.

Figure 1.1 The core of the research framework: enactors, selectors and expectations as linchpin

Research question

Unlike evolution in a biological sense, variation and selection in innovation processes are not blind and both enactors and selectors are able to anticipate each other's assessments and decisions. In the case of emerging technologies, variation and selection take place before the market is entered and expectations are likely to play a key role. Emerging technological options thus compete on the basis of expectations of future performance levels, rather than on the basis of known price and performance characteristics.

The combined research framework of quasi-evolutionary technological change, technological expectations, and technological communities, is the starting point to study the pre-market competition between different technological options in more detail. The central research question thus reads:

How do emerging technologies compete?

This question needs to be broken down into sub-questions. Following the research framework, it should first be clear who the enactors and selectors are and how the distinction between them is to be understood:

How can enactors and selectors be characterized?

Then the question is how both groups of actors actually raise and assess the various expectations:

How do enactors try to shape expectations of their technological options?

How do selectors make assessments of those expectations?

1.3 The hydrogen car as a prospective structure

To answer these questions, the development of the hydrogen car is used as a case study. The hydrogen car is indeed an emerging technology, or better: a set of emerging technologies, and its development show both competition on a system-level, of the different cars of the future, and on a component-level, of the different enabling technologies that are needed to make the hydrogen car 'work'.
Because of diminishing oil supplies and expected increases in emissions regulations, the car industry is developing cars with tank-to-wheel efficiencies and lower emissions. First of all a so-called sailing-ship effect can be recognized as the car industry tries to enhance its current dominant design (Dijk 2010, Lee et al 2010). Options such as stop-start systems make that the current design can operate more efficiently. And, the use of alternative fuels in the conventional drivetrain, biofuels and natural gas, results in lower emissions as well. The hydrogen car is one of the more radical options that the car industry also explores. It is a radical innovation (Henderson and Clark 1990), as compared to the gasoline-powered internal combustion engine, as both the core components of the hydrogen car are different from today's car and also an entirely new infrastructure is needed.

The car as we know it reaps the benefits of its dominant position. About 50 million passenger cars are produced each year[2] and economies of scale and highly robotized factories make that these cars are relatively cheap to produce. The infrastructure is well laid-out and consumers can fuel their car anywhere and at any time. Drivers know what their car is capable of and they know how to operate it. Furthermore, well-spread networks of dealerships and repair shops make the car is available everywhere and most problems can be solved by most repair men.
For any 'car of the future' the challenge is thus to break through this lock-in. The current candidates for the car of the future lack scale benefits, lack infrastructures, and there is no clear picture what these cars will be capable of and there is hardly a network of skilled service engineers. Furthermore, safety guidelines are lacking, fuel standards are lacking, emergency personal is not trained nor equipped to deal with hydrogen car accidents, etc.
The most pressing issue is probably the build-up of a refuelling infrastructure. Whereas the today's cars can refuel on just about every street corner, hydrogen car drivers are lucky to find one within hundred kilometres of their homes. This results in a chicken-and-egg problem: without gas stations no one will buy a hydrogen car and without hydrogen cars, no gas stations will be built. Governments

2 Detailed production statistics can be found on: www.oica.net/category/production-statistics/

may take a lead in overcoming the dilemma, but this is just one example of the problems that any locked-out technology faces in its infant stages.

In the meantime, the proponents of the hydrogen car try to convince that hydrogen is the most promising fuel of the future and that the hydrogen car is the most promising, and possibly the only, solution to the problems that the car industry faces.

The most abundant element

Hydrogen is the most abundant element in the universe. This tagline is often used by hydrogen proponents to start their plea on behalf of their favourite molecule. The fact that elementary hydrogen is abundant means nothing more and nothing less than that it is available for use in an energy cycle, a very versatile energy cycle indeed.

Basically, the interest is in the reaction of hydrogen, in its molecular form H_2, with oxygen. This oxidation results in water and energy and makes that hydrogen can be used as an emissions-free fuel. However, molecular hydrogen is far from abundant and needs to be produced. The versatility of the cycle is found in the wide variety of (energy) sources that can be used to produce hydrogen and in the range of applications for which hydrogen can serve a fuel.

Hydrogen is thus not a sustainable energy *source*, but hydrogen could serve an important role as *carrier* in a sustainable energy system. Many renewable energy sources are unpredictable and intermittent and hydrogen can be used as a storage medium that can bridge time and space between production and use. And, hydrogen can be used to replace the liquid fossil fuels that are used in today's vehicles.

However, hydrogen cars and related (infrastructural) hydrogen technologies are in a stage of development and different visions of hydrogen futures circulate still. Nothing is certain and different stories about possible futures are filled with a multitude of technological components and together these shape a range of imagined hydrogen futures.

To provide a basis for the rest of this thesis, a short introduction to the various hydrogen visions is presented in the remainder of this section.

Visions of hydrogen as a sustainable energy carrier

When one has an interest in promises and expectations of emerging technologies, vision reports and statements are good starting points. For hydrogen, various visions circulate in formal foresight documents and more informally in books and on conferences etc. These visions relate to expectations of the technologies as well as to society as a whole. In the first category, visions of the future are down to earth and focus on the development of certain technologies and routes for the deployment of hydrogen infrastructure (Ogden 1999). In the second category however, visions on the whole of society are taken into account and hydrogen is therein not just the replacement for fossil fuels but also the fuel for enormous societal changes (Rifkin 2002). Even though the visions are diverse, there is a common set of arguments that stands out.

The need for an alternative to fossil fuels is the most prominent argument to support hydrogen visions. While this argument may seem clear, it does not necessarily justify the belief in hydrogen and the

complex constructions of diverse expectations that are used. The complexity stems from the fact that energy systems are by definition formed by interlinked and interdependent sets of technologies, actors, and institutions. Even more so, hydrogen technologies are currently underdeveloped in every part of the system and far from economically competitive. Besides that, the enormous economical and political interests that are associated with the current energy system make that any alternative, including hydrogen, will face significant resistance (Unruh 2000). The speeds with which oil and fossil fuels are running out is not clear either (Smil 2000) and serious supply problems are not around yet.
Thus, both from a technological as well as from a systemic perspective, it is clear that the credibility of any hydrogen vision is highly contested for the short to medium term. As a consequence, both extremely optimistic visionaries such as Jeremy Rifkin (Rifkin 2002) as well as criticasters such as Joseph Romm (Romm 2005) can write and sell books with completely opposing conclusions. In the mean time, many believe that hydrogen is above all an excuse for the industry to do research instead of actually aiming to develop and commercialize more sustainable cars. That is, hydrogen has been a promising energy carrier for over forty years and it has drawn much governmental funding for R&D. But the firms that have taken advantage of this funding have not come up with any commercial applications. Sceptics argue that this is no coincidence and claim that the (automotive) industry has also held off more stringent regulation with regard to hydrogen- and other low- or zero-emission vehicles (Vaitheeswaran and Carson 2008).

Still, hydrogen has been on the energy agenda for at least four decades (Dignum and Verbong 2008, Hultman 2009). The visions of hydrogen as an important alternative arose for the first time when fuel cells were developed (Eisler 2009) and nuclear energy promised to be an endless, clean and cheap supplier of electricity (Marchetti 1976). The combination of these technologies was the seed for the vision. The need for an alternative to fossil fuels can be seen as a fertilizer. The development of the vision thus includes a bottom-up move for the application of new technologies (nuclear power and fuel cells) and a top-down move for an energy regime change. Today one can distinguish between three general rationales or '*leitbilder*' for hydrogen visions: resource depletion & climate change, energy security, and decentralization of the energy system (Eames et al 2006).
For hydrogen energy systems, a bit more is needed than just the energy source and fuel cells. A number of enabling technologies, such as for storage and distribution, are recognized as being important for the feasibility of hydrogen energy systems as well. Over the years these enabling technologies were proven to be problematic however. They require significant further improvements and they have subsequently taken a more central role in the visions, research agendas, and technological roadmaps towards the realization of the visions.

The Prospective chain of hydrogen technologies

In the following the different enabling technologies and systems are discussed and it is argued that these are competing among one another. These technologies are part of wider hydrogen visions that also compete with each other. First of all a distinction can be made between stationary and mobile applications of hydrogen. In stationary applications the hydrogen is used as an energy carrier, or storage medium, to power the built-environment. In this thesis the focus is on mobile applications and ultimately on automotive applications. Therefore, the set of technologies that could be used to make a hydrogen car are discussed here.

From a number of hydrogen vision reports (Department of Energy 2002; Duwe 2003; European Commission 2003; HFP 2005; Commission 2006) one can conclude that the hydrogen energy system is commonly divided into four main components:

- Production
- Distribution
- Storage
- Use

Together, these components constitute hydrogen energy systems. Every hydrogen vision document agrees on the need for all four of these components and their integration into a new energy system. The vision reports are less clear, however, about the individual technological solutions for each of the links in the hydrogen chain. Because of the relatively underdeveloped status of these solutions, in comparison to commonly used energy systems, it is hard to select the winners beforehand. The uncertainty over the potential of individual solutions feeds competition between actors and organizations working on their development.

Vision documents present the technologies as almost interchangeable and the focus is on delivering the best solution to hydrogen's needs. The more promising any of the technologies is, the better it is for hydrogen. What is under the surface of the documents however, is the competition between the technologies. They are presented as colleagues working towards the same goal, but in practice they are competitors just as much. The selection of hydrogen technologies can thus be represented as a chain of functional components that has to be filled in by concrete, but currently competing, technological solutions. This chain however is only a *prospective chain* as it is only a projection of things that might come to being (Figure 1.2). Note here that in terms of the sociology of expectations, the prospective chain of hydrogen technologies is a *prospective structure* for current activities. It needs to be filled in with concrete technologies: it shapes a research and development agenda.

To determine which technological options should be part of the research agenda, the options are continuously assessed for their fitness in relation to the prospective chain. Both the enaction as well as the selection takes place even though none of the actors know exactly what specifications will be required in the future.

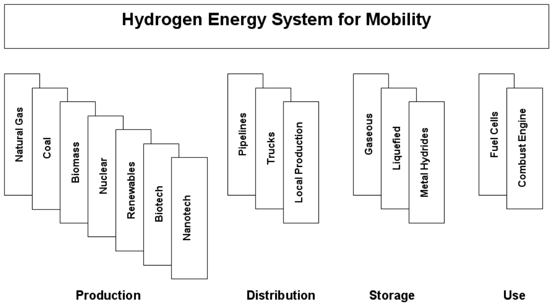

Figure 1.2: The prospective chain of hydrogen technologies for mobile applications.

From the studied vision reports a number of potential solutions are derived that are in the running to become the leading solution in the prospective hydrogen chain. These bids are interrelated and some solutions in fact pre-select one another. For instance, fuel cells require highly purified hydrogen gas and some production methods are more suitable to meet these requirements; electrolysis produces much purer hydrogen than steam reforming of natural gas.

An overview of the most prominent options and the 'common expectations' about these, as they appear in the aforementioned vision reports, is presented in Table 1.1. With the exception of natural gas reforming, none of these technologies is currently commercially available or 'ready' to function without further development, adaptation or testing. They are either too expensive, not energy-efficient enough or have not proven to work at all.

For the hydrogen car, as a configuration of these components, this means that even though these cars 'work', they are not truly suitable for commercial introduction yet. Today, the hydrogen car is, again according to the vision reports, still too expensive, its energy efficiency could or should become higher, its range is limited, hydrogen is still expensive and hard to come by in the absence of a refuelling infrastructure, there are questions about safety, and the reliability of the drivetrain is somewhat uncertain.

Because none of the enabling technologies is seen as 'ready', a wide variety of enabling technologies is being developed in the hope that one will be good enough, eventually. On the one hand this sends a message of versatility: hydrogen can be produced from anything, it can be stored in anything, and it can be used for everything. But, on the other hand, there is also the message of the infant stage of hydrogen technologies: there are many possibilities, but so far none of those is good enough. The versatility of hydrogen makes it such an attractive energy carrier (Sperling and Ogden 2004), but this message of hope is balanced by the 'underdeveloped' state of its enabling technologies. In other words, the components of the hydrogen car can be configured into a highly desirable vision, but also a vision that entails a lot of work to make the vision come true.

Table 1.1: Overview of possible solutions and 'common expectations'

Element	Solution	Expected capabilities
Production	Natural Gas (with CCS)	Steam-reforming of natural gas is the most common production method and it is expected to remain so for a couple of decades. With the addition of CCS this could be near climate neutral.
	Coal (with CCS)	Costs are similar to hydrogen from natural gas, but energy efficiencies are somewhat lower. Societal acceptance of using coal is questionable. Coals supplies may last longer than NG.
	Nuclear	Nuclear energy might be used to produce hydrogen through electrolysis, but this is a costly and inefficient route. Direct use of nuclear heat for thermal hydrogen production from water might ever be a feasible route, but this will not be available for some decades.
	Biomass	Biomass can also be used for steam reforming. The energy efficiency of this pathway is questionable, and so is the amount of biomass available for this purpose.
	Electricity from renewable sources	Like nuclear electricity, costs are too high at this point to use this electricity to produce hydrogen. Hydrogen might be used as storage medium in times of overcapacity. A lot is expected from further technological development of electrolysers and economies of scale.
	Laboratory stage methods	Methods that can be qualified as futuristic come from biotechnology (production by micro-organisms), nanotechnology (more efficient electrolysis on nano-materials). Thermal splitting of water using concentrated solar energy is a prominent futuristic solution that could be used to produce large quantities of hydrogen at low cost.
Distribution	Pipeline delivery	Use of pipelines would be the most efficient means of transport in case of centralized hydrogen production. Deployment of this infrastructure would require sufficient demand for hydrogen and probably many years if not decades for its construction.
	Truck delivery	A proven method for delivery of hydrogen and a probable solution for a transition period in case of centralized production.
	On-site production	Often used for demonstration projects, with natural gas reforming and electrolysis, but for the long term only realistic if costs are lowered dramatically.
Storage	Compressed gas	Well known technology, but highly inefficient in terms of energy and required volume. The required high pressures cause some safety concerns.
	Liquid hydrogen	Complex and costly method for storing large amounts of hydrogen. Proven technology, but highly inefficient in terms of costs and energy.
	Metal hydrides	Complex and underdeveloped method. But holds a promise of efficiency in terms of energy and volumetric density.
	Chemical Storage	Liquid chemicals can also be used to store the hydrogen with high volumetric density. On-board of the vehicle a reversed chemical reaction can be used to free the hydrogen. The remaining chemical compounds can than either be emitted or recycled. Obviously this presents some environmental issues.

Use[3]	Fuel Cells (multiple types)	Although expensive and heavy, Fuel Cells are the flagship technology of the hydrogen vision. Different types use different membrane materials and have varying efficiencies and operating temperatures. A price drop is expected when production rises.
	Internal Combustion Engine	Proven technology that appeals to cultural annotations of the car. Less efficient than Fuel Cells, but cheaper to built.

1.4 Case selection and research methodology

To study the multifaceted competition between emerging hydrogen technologies, different (sub-) cases were selected to elaborate and unravel the dynamics. These cases were selected on the basis of two dimensions of the competition between emerging technologies, as discussed above. The first axis relates to the distinction between the enactors and the selectors. On the second axis is the distinction between the system-level and the component-level. Together these axes shape four quadrants in which the competition is played out and that had to be covered by the different cases. While the distinction between enactors and selectors was sufficiently discussed in Section 1.2, the distinction between the levels of systems and components in relation to technological expectations calls for an additional elaboration.

Levels of competition and levels of expectations

A number of scholars have proposed to define different categories of expectations. Van Lente (1993) proposed a distinction between three levels, ranging from specific, to functional, to scenario-like expectations. Along the same lines, Ruef and Markard (2010) distinguish between (actor-) specific expectations at the level of technological options, generalised expectations about the functionality of the technology, and frames, scenario or vision-like expectations that include the wider (future) context. Budde (2009) suggests to follow the distinction between the niche, regime and landscape level as they are used in the multi-level perspective (Geels 2002). Thus, various typologies of expectations and activities are available.

For the case of hydrogen technologies, as they are so much imbedded in a nested hierarchy of components and systems, it seems appropriate to study two levels of competition. Hence, the competition between different system-options should be studied, as well as the competition between different component options. At the same time, it is appropriate to define levels of expectations in a similar vein and to distinguish between the environment, the system and the component as relevant levels of expectations for the hydrogen car. Expectations with regard to the *environment* relate to future selection criteria for the car of the future. These are thus expectations about future oil prices, security of gasoline supplies, environmental issues that may result in changing consumer preferences and governmental regulations. Expectations about the *system* relate to configurations of multiple

3 The component 'use' is also called 'conversion' in this thesis. The latter term refers to the conversion of hydrogen into usable forms of energy to propel a vehicle.

components and include the hydrogen car mostly. The *component* level includes the individual technological options such as they were distinguished in the introductory chapter.

Both the system and component levels are studied explicitly in the case studies. The level of the environment also features in the case studies, but it less relevant for the selection of case studies since expectations of the environment have, by and large, similar effects on all technological options: they create a generic window of opportunity for low- or zero-emission vehicles.

The case studies

To do justice to the richness and complexity of the subject, different perspectives are taken and different sets empirical material and research methodologies are used. In the following the chapters are introduced shortly and related to the four quadrants as outlined above (see also Figure 1.3). More detailed accounts of research methodologies are provided in the respective chapters.

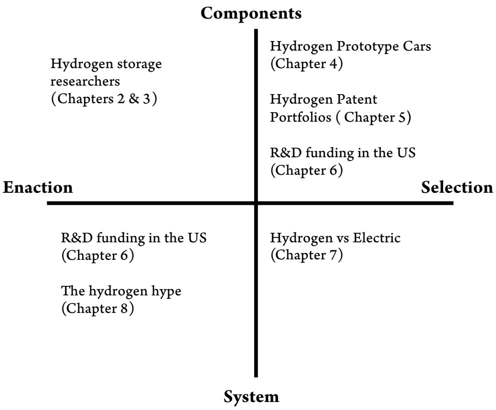

Figure 1.3: The distribution of cases (and the respective chapter numbers) along the enaction-selection and the components-system axes.

With hydrogen storage generally seen as the most challenging component, where the competition in terms of activities and expectations is intense and visible, it takes a central role in most of the chapters. The community of metal hydrides researchers is taken as a first case to understand what 'expectations work' (van Lente and Rip 1998a) entails and, be it to a lesser extent, how their expectations work is assessed by their sponsors (Chapters 2 and 3). In Chapter 2 the focus is on the elaboration of the research framework and the concept of 'Arenas of Expectations' is proposed to investigate and understand the exchange and accumulation of expectations of emerging technologies. In Chapter 3 an extension to the 'phases of innovation' model of Utterback (1994) is proposed. Whereas the Utterback-model takes into account only those phases of the innovation process in which the market is involved, here an earlier *expectations phase* is added. Researchers' claims on the future potential of metal hydrides, in their scientific articles, are measured and analyzed with the help of a Toulmin scheme of argumentation.

Hydrogen storage also features as the most prominent component in the case studies with a stronger focus on the selectors. Prototypes and patents are used as indicators of the expectations and actual selections that car manufacturers have made in the diverse component technologies. It is argued that the use of prototypes and patents as proxies for expectations provides an opportunity to quantify expectations, whereas the sociology of expectations is often limited to qualitative analyses.

Especially in the chapter on prototypes it is also studied how the firms have made their selection decisions and how this is both cause and consequence of the expectations work throughout the industry (Chapters 4 and 5). Theoretically, in Chapter 4, it is shown how in the pre-market phase variation and selection take place and different firms converge to a preliminary dominant design. By doing so, dominant design theory is enriched with an understanding of the pre-market dynamics that guide the selection in the absence of market forces. In Chapter 5 it is studied whether the same dynamics can be found in car manufacturers' patent portfolios and whether this is an indication of the distance to commercialization for hydrogen cars.

Storage is again of interest in Chapter 6. Here the US Department of Energy's Hydrogen Program is studied, through policy documents and minutes of meetings, and it is shown how it performs both the role of enactor as well as the role of selector. It selects component options that are thought to be promising and it attempts to enact the hydrogen car towards the Department's and federal government's leadership. In this chapter it is questioned how actors decided on the credibility of any technological expectation and how a 'credible expectation' is constructed.

Chapters 7 and 8 are both concerned with the hydrogen car on the system-level. Chapter 7 deals with the competition between the hydrogen and the battery-electric car and it shows that both options have alternated in terms of attention from the car manufacturers and that they actually compete with each other. The competition is studied from the perspective of sociotechnical transitions and it is questioned how such competing transition trajectories interact and compete and what the role of expectations and design rules is. The analysis in Chapter 7 is based on an analysis of *AutoWeek* articles and the prototypes that are mentioned are based on those that are published in this magazine. The dataset of prototypes that is used, or referred to, in Chapters 4, 5, and 8 is build from a wider range of sources and holds a larger number prototypes as a result.

Chapter 8 deals with the car industry's role as enactor of the hydrogen car. It shows how the industry has over-promised with regard to hydrogen vehicles and how this has resulted in a phase of hype and subsequently in the current phase of disappointment. Finally, Chapter 9 concludes with a summary of the findings, a reflection on the central framework and a discussion of the contribution of this thesis to studies of innovation and expectations.

2. Arenas of Expectations for hydrogen storage

2.1 Introduction[4]

It is a truism that technological change proceeds with trial and error. Technological development or innovation is often described as a continuing evolutionary process of variation, selection and retention (Dosi and Nelson 1994, Nelson and Winter 1977). Different technologies are seen as the variations, while the market, in a broad sense, is their selection environment. Successful innovations are assumed to fit best with their given markets. In the selection environment choices are made between different technological options at the level of individual technologies, and, eventually, at the level of sociotechnical systems (Geels 2006). The evolutionary process of variation and selection thus assumes competition between the various emerging technologies. While the evolutionary perspective has proved to be fertile and has lead to important further insights and new policy inspiration (Geels 2006, Suurs 2009) it also raises the problem *how variation and selection are related*. A strict evolutionary metaphor for technological change must be inappropriate, since variations are not blind and selection is not fully independent. The *quasi*-evolutionary model introduces the role of agency and stresses the connection between variation and selection through anticipation and strategies of various actors (van den Belt and Rip 1987, Schot 1992, Rip et al. 1995). Actors anticipate the selection environment because they have some understanding of its future demands, for instance by extrapolating ongoing improvements. Actors will also seek to modify selection environments, by voicing expectations or with other moves like forging strategic alliances. The quasi-evolutionary approach, thus, provides us with a model of technological development and competition that is not dependent on spontaneous, blind variation, but instead relies on guided search through different heuristics and on strategic moves to shape the selection environment. According to the quasi-evolutionary model, variation and

4 This chapter is published as: Bakker, S., van Lente, H. & Meeus, M. (in print - available online) Arenas of Expectations for Hydrogen Technologies, *Technological Forecasting & Social Change*

selection are interrelated and embedded in a so-called '*cultural matrix of expectations*'(van den Belt and Rip 1987 p.155). This matrix is the set of expectations about the variations and about the selection environment they have to fit. And, the heuristics that guide technological development are embedded in this matrix, according to Rip and van de Belt.

A further elaboration of the interplay between variation and selection is developed by Garud and Ahlstrom (1997). They argue that a socio-cognitive 'game' is played between, on the one hand, actors that create or 'enact' technological development ('enactors' as suggested by Rip (2006) and, on the other hand, actors that select technologies according to their criteria ('selectors'). Enactors create and put forward technological variations that they claim to be solutions to perceived problems. Selectors, however, start with their (often different) perception of the problem that needs to be solved, and assess how various technologies may contribute to a solution. Note the differences in degrees of freedom between enactors and selectors: the fate of enactors is much more related to the success of one or more technologies, while selectors can afford to be much more indifferent to the fate of a particular technology. According to Garud and Ahlstrom, enactors and selectors meet in so-called 'bridging events' such as funding decisions or technology assessment exercises.

In this paper we aim to develop further the understanding of the role of expectations in the enaction and selection of emerging technologies. Our claim is that the quasi-evolutionary framework does address the role of expectations, but less clearly the question of how expectations are put forward and how they are assessed. This is especially problematic in those cases in which multiple technological options compete for selection. In such cases, the enactors need to position their option in relation to other options, and selectors need to select those options that they deem most viable.

Hence, we propose a next step and argue that variation and selection of future technologies connect through expectations and we introduce the concept of '*arenas of expectations*'. The arenas of expectations are then the linchpins between those actors that enact their technological options and those actors that select the most promising options. In the arenas of expectations, claims about future technological options are launched, compared, elaborated and assessed. In the next section we first elaborate on the role of expectations in innovation processes following the relevant strands from the literature, in particular the sociology of expectations and we relate this to the literature on technological communities and R&D evaluation. We present a case study in which the confrontation between variation and selection can be traced for several decades (Sections 2.3 and 2.4). It concerns a particular technological variation to store hydrogen in vehicles. Storing large enough quantities of hydrogen on board of vehicles is crucial within the vision of hydrogen as the fuel of the future. Yet hydrogen storage remains rather problematic thus far (Bakker 2010). The community of researchers working on metal hydrides claims that hydrides might solve the storage problem in the future. In this way they remain visible in the different roadmaps and foresight reports, and secure their position on research agendas and ultimately receive funding for their work. We studied the expectations work of the metal hydrides community and the various anticipated and actual confrontations with their competitors and their selectors in arenas of expectations.

The paper concludes with a further reflection on the role of agency and expectations in the co-evolution of technological variations and their selection environment. In the resulting framework of '*arenas of expectations*', 'enactors' (i.e. communities that develop technological variations) feed and test the future outlooks of a technology vis-à-vis the concerns and hopes of technology 'selectors'.

2.2 Expectations and communities

Expectations are of great importance for the development of technologies as they stimulate, steer and coordinate action of actors (Borup et al 2006). The idea of expectations as key element of technological innovation was examined by Van Lente (1993, 1998b), and has been developed into a 'sociology of expectations' (Borup et al 2006, Brown and Michael 2003). A working definition of technological expectations, in the context of innovation, is provided by Borup et al (Borup et al 2006): technological expectations are real-time representations of future technological situations and capabilities. That is, it is a combination of expected progress of the technology at stake, its future markets, and its societal contexts. Promises and expectations of emerging technologies are part of an agenda setting process (Guice 1999) and thereby help to create a *mandate* for engineers and other actors (van Lente 2000). This mandate, in terms of funding and other forms of credit, gives them the opportunity to continue the development of 'their' technology. A mandate, by definition, comes with requirements that should be met: expectations and promises lead to requirements. Steering and coordination of action is done through the voicing of and responding to expectations as well. Coordination can be achieved when expectations are common reference points for actors in different communities or different levels of technology development (Borup et al 2006, Konrad 2006).

Expectations inform all parties, but they are not automatically accepted at face value, of course. On both sides, criteria are used to assess variations, both in terms of expected performance (ex-ante) as well as in terms of actual performance (ex-post). These criteria however are not necessarily stable and shared by all actors, as many studies of technology have shown (Bijker 1995, Garud and Rappa 1994). As a consequence, criteria are shaped by actors' needs, vested interests, lobbying and learning processes. There is not one best technological solution to a single problem: for different actors, different technologies fit best. Enactors, for instance, will stress the criteria that will favour their particular variation. Technology selectors, on the other hand, have to balance a number of, sometimes contradicting, criteria and this balance could very well shift over time. The outcomes of processes of quasi-evolution of technology are therefore as much determined by social processes, such as strategic games and the construction of needs and selection criteria, as they are by material characteristics (Pinch and Bijker 1984).

The role of expectations is most pertinent in the earliest phases of the innovation process. Sometimes, selectors judge technological options on facts, specifications, and actual proofs of the usefulness and economics of variations. In the bicycle case presented by Bijker (1995) for instance, artefacts are judged on actual performance and interpretations. Even though different users (end-stage selectors) have different perceptions of what a bicycle is and should do, the bicycle models could be tried and tested in practice.

In the case of emerging technologies and sociotechnical systems, however, investment decisions (and other pre-selections) have to be taken in an early stage of development, when the technologies are not yet prone to such trials of actual performance. In this situation uncertainty is much higher and actors have to make decisions based on expectations rather than facts (Glynn 2002). In the case of hydrogen technologies, numerous technological capabilities and societal aspects are indeed very uncertain. In some niche markets, commercial applications are used already, but the first commercially viable hydrogen car has yet to be built. A lot is known about the laboratory performance and specifications, a bit less about prototypes, but far less has been learned about real-life use, system integration, possible learning curves, and economies of scale. Expectations of possible improvements are thus the only basis for decisions to be taken in this phase, for enactors and selectors alike.

As many emerging technologies are highly complex and systemic in nature, it takes a multitude of actors and organisations to develop the actual technologies and make them work. One conceptualization of such groups of actors and organisations is provided in the literature on technological communities (Rappa and Debackere 1992, Debackere and Rappa 1994, Lynn et al 1998, Rosenkopf and Tushman 1998). The concept of technological (or innovation (Lynn et al 1996)) communities is used to describe and understand the inter-actor and inter-organizational behaviour in innovation. According to Rappa and Debackere, technological communities can be defined as:

"group of scientists and engineers, who are working towards solving an interrelated set of technological problems and who may be organisationally and geographically dispersed but who nevertheless communicate with each other" (Rappa and Debackere 1992 p.210)

This definition is applicable to the group of scientists and engineers who work on the different component technologies for the hydrogen energy system. They are globally dispersed but have a shared goal to develop solutions and a shared interest in convincing technology selectors of the future potential of their work. Most of this body of literature is concerned with the co-evolution of communities, 'their' technologies and their competition with other communities (Lynn et al 1998). How these communities use expectations and promises in this competition has received less attention. We argue that expectations work, next to technological success, is important to the growth and success of any technological community.

For a specific technology, there is a technological community working on the concomitant technological options, consisting of researchers in academic science, research institutes and industry. From the literature we take two characteristics of technological communities. The first is the composition of a community. The major distinction is between members from academia and members from industry, given the difference in (community) behaviour displayed by these two groups, which is a relevant distinction because it will have an effect on 'expectations work'. Scientists tend to maintain positive expectations as long as these provide them with a mandate and with funding to continue their research activities. For industry it seems that meeting expectations is more vital and hence they tend to compare and test expectations.

The second community characteristic derived from the literature deals with the type of binding factor in the community. Academics are in general concerned with a specific field of knowledge (their specialism or 'paradigm') whereas industrial actors care about finding solutions that work for the constellations they are interested in. In other words, a dominantly academic community focuses on a specific area that promises to be relevant, in the end, for a wide and relatively unspecified set of problems. An industry dominated technological community, on the other hand, is bound by the search for means to meet a goal, and based on the community's competencies or other grounds. In the literature this distinction has been characterized as between paradigm-driven versus solution-driven communities, or between design-based versus sponsor-based communities (Wade 1995).

Furthermore, it is stressed that a technological community is a heterogeneous entity and that actors have different roles within the community. One could expect, for instance, a hierarchical distance between leaders and spokespersons on the one hand, and, on the other hand, scientists and engineers that are mainly concerned with the work floor. A community leader, say, a highly respected professor, is more likely to engage in explicit expectations work than a laboratory analyst. Also, the personal expectations held within the community might differ (Berkhout 2006).

2.3 Chained expectations of hydrogen technologies

In the wider community of hydrogen technology developers, many different technological communities are at work for specific technological options. Together, these communities are in competition with other communities that develop alternative cars of the future, such as electric and biofuel vehicles. At the same time, the hydrogen communities are in competition with each other over the question: who is working on the most promising solution?

As a result, different interpretations of the 'hydrogen vision' circulate. And, while car manufacturers claim to be working on the commercialization of hydrogen vehicles and hydrogen demonstration projects are set up worldwide, the future of a 'hydrogen economy' is still highly uncertain. In hydrogen vision reports (Department of Energy 2002, Duwe 2003, HFP 2005, European Commission 2006, Marshall 2006, Vermeulen 2006) a number of similar, yet slightly different visions are explicated (McDowall and Eames 2006). These visions aim at mobilizing support for hydrogen technologies, as hydrogen is not the only contender in the race for the fuel of the future. For mobile applications, hydrogen faces competition from, amongst others, bio fuels and various types of battery electric vehicles (van Bree et al 2010, Oltra and Saint Jean 2009).

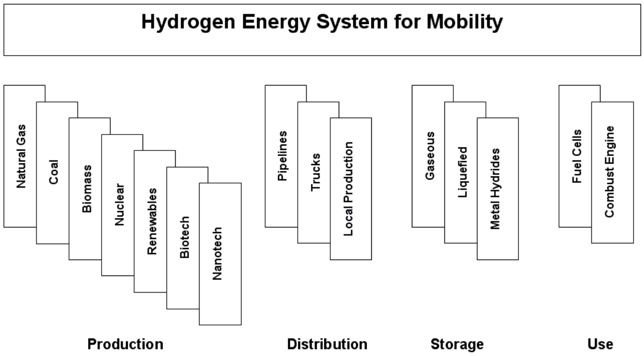

Figure 2.1 The prospective chain of hydrogen energy technologies. It contains the four main elements (production, distribution, storage and use) for which a number of 'promising' options are put forward.

Given the large uncertainties about the future of energy production and consumption, the hydrogen visions tend to be rather open and ill-defined in terms of specific technological solutions.
This openness leaves room for interpretation and incites a competition between different specific proposed solutions for the various challenges. As a result, enactors are faced with a fundamental ambiguity: hydrogen proponents, on the one hand, compete with other hydrogen technologies: on the other hand, they need to downplay the competition to convince outsiders of the future possibilities of hydrogen in general. They can claim or colonize (Brown and Michael 2003) their share in the future of transportation energy systems and use all kinds of arguments to support hydrogen and to build on a number of positive images of hydrogen technologies (Eames et al 2006). To make the hydrogen vision(s) credible, proponents and other interested actors need to show the technological possibilities of the hydrogen energy system in its entirety. Commonly, the envisioned hydrogen energy system is divided info four main elements: production, distribution, storage and end-use. For each of these four elements a number of enabling technologies and approaches are proposed as viable candidates. Hydrogen technologies are thus arranged in a nested hierarchy of system, subsystem and component technologies (Murmann and Frenken 2006).

Currently, none of these technologies, subsystems or systems is 'ready' for implementation without further development, testing or adaptation. At least for vehicular use, they are either too expensive, not efficient enough or have not proven to work at all[5]. The configuration of elements of the hydrogen vision is what we define as the *prospective chain* of hydrogen technologies. It is not in existence yet, but it is a projection of things that could come into being and hence it is fundamentally prospective. In all hydrogen visions the prospective chain, or variants of it, is filled in with interdependent promising technologies. Figure 2.1 depicts the prospective chain with the most common 'promising' technological options for each of the elements (van Lente and Bakker 2010). The options range from

5 Hydrogen is already produced at large scale in the petrochemical industry by means of reforming natural gas. For use as car fuel this process is still too expensive to compete with gasoline in today's market.

rather short-term ('almost ready') options such as hydrogen production from natural gas, to truly long-term and highly uncertain options such as hydrogen production with the help of nanotech solar panels or genetically modified algae.

Despite the fact that none of these technologies is truly satisfying and commercially available, hydrogen visions have to build upon them for their credibility. This implies that hydrogen visionaries and other proponents necessarily create and maintain expectations about component technologies as well about a hydrogen energy system or even a 'hydrogen economy'. The chain of technologies is thus repeated as a chain of interdependent expectations. Note the double bind: the viability of the hydrogen vision is dependent upon expectations of individual components and the redundancy that is provided by the multitude of options per element, while the credibility of singular hydrogen technologies is derived from their contribution to the hydrogen vision at large.

2.4 Expectations work for metal hydrides

To study the dynamics of variation and selection on the basis of expectations in more detail, we have performed a case study on one of the hydrogen technological communities, which proposes to store hydrogen in the atomic lattices of metal alloys: metal hydrides. This community pursues the storage of larger quantities of hydrogen on board of a vehicle, thereby enlarging the cars driving range. So far however, metal hydrides researchers have not found what they are looking for. Still, they can continue their work as long as their sponsors accept the promises and expectations of their quest for better alloys and catalysts.

Our case study builds on a literature study as well as a series of interviews with metal hydrides researchers. The first part of the case study aims at identifying the position of metal hydrides in the hydrogen vision. From there on we reconstruct the history of the metal hydrides at the level of the technological community and its expectations work in enacting metal hydrides as a promising option as compared to its competitors. In a next section we zoom in on the individual researchers and their anticipations of the selection process. Finally we conclude the case study with a description of the technology selectors and their assessments of the promise of metal hydrides.

Metal hydrides and the hydrogen vision

Results of foresight activities on the future hydrogen energy system can be found in many loci: in governmental reports, scientific journals, in engineering circles as well as in popular press. A favoured way to plot the future of hydrogen is to use technology roadmaps (Phaal et al 2004) and other outcomes of foresight activities (Webster 1999). We have selected six (Department of Energy 2002, Duwe 2003, HFP 2005, European Commission 2006, Marshall 2006, Vermeulen 2006) hydrogen vision reports and technological roadmaps from different geographical regions and stakeholder groups to position metal hydrides within the hydrogen vision. While these reports sketch the background to our case study, they also expose some of the assessments, of metal hydrides expectations, made by technology selectors. We discuss these assessments at the end of this section, but for now the focus is on the position and expectations work of the enactors.

Typically, the reports mention three basic options for on board storage that are in competition with each other and therefore are relevant to our case study: liquid storage (LH), gaseous storage (GH) and storage in various metal alloys, typically named metal hydrides (MH). Other proposed solutions are much less mentioned, such as storage in nanoparticles (nanotubes) or storage of hydrogen atoms bonded in liquid substances (to be added and removed through chemical reactions). The visions and roadmaps seem to agree on what to expect from the three main solutions of hydrogen storage. All solutions have their own (fundamental) pros and cons and these figure repeatedly in the reports and other literature. The vision reports can be taken as a representation of the trials of strength between the different enacting communities and their selectors. Based on those reports, we draw a number of conclusions in relation to hydrogen storage options.

First of all, the on-board storage of hydrogen is presented as one of the biggest challenges for the use of hydrogen as energy carrier for mobility. Liquid hydrogen scores very well in terms of volume and weight, but is inefficient in terms of energy: 30% of the energy is lost due to the low critical temperature of liquid hydrogen (Department of Energy 2002). Gaseous hydrogen leads to better energy efficiency and is used in practically all hydrogen prototype vehicles (with the exception of BMW's liquid storage[6]). The gas is pressurized up to 700 bar, resulting in acceptable volumetric densities, but this process consumes about 20% of the energy. Safety concerns and production costs, however, add to the doubts about this solution. In terms of expectations voiced in the documents, liquid and pressurized storage are not seen as very promising. The drawbacks are seen to be caused by thermodynamic laws: pressurizing gas takes energy, and liquefying even more. Although some researchers from these communities work on ways to regenerate the energy, there does not seem to be a lot of room for improvement. Research on gaseous and liquid tank designs focuses mainly on cost reductions and safety improvements. Metal hydrides are, in contrast, less understood and this seems to be their main source of promises: there is a lot to learn and therefore a great potential for improvement. The documents all mention the underdeveloped stage of metal hydrides and at the same time also stress their future potential as compact and energy efficient method for storing large quantities of hydrogen. In other words: metal hydrides might be the '*Holy Grail*' of hydrogen storage but the right alloy has not yet been discovered.

The metal hydrides community

The metal hydrides community has actively engaged in expectations work towards its selectors in order to gain and maintain a position on the research agendas. As said, we have performed both a concise literature study and a series of interviews to reconstruct their work towards that goal. The literature study included four review articles on metal hydrides research (Buchner 1980, Peschka 1987, Güther

6 By means of an internet search we found 3 metal hydrides prototypes built by major car companies (Daimler-Benz in the 1980's and Toyota in 1996 and 2001), on a total of about 250 hydrogen cars. With the exception of BMW all manufactures use gaseous storage with pressures of either 300 or 700 bar.

and Otto 1999, Chandra et al 2006). The semi-structured interviews were held with eight senior metal hydrides researchers in the Netherlands. All of them participate in the so-called 'Sustainable Hydrogen' research program which is financed by the Netherlands Organisation for Scientific Research (NWO). About half of the projects financed by this program, originally set up to finance research in chemistry, deals with metal hydrides research. The interviewees' research varies from experimental work on new material compositions, to new production methods and computational modelling of the hydration processes and thereby it covers the main subfields of metal hydrides research as found in the review articles.

During the interviews we discussed their activities in communicating expectations to their peers and technology selectors in the different arenas and this helped us to analyse the mandating and constraining process. The interviews also allowed us to reconstruct their framing of the competition between the different storage solutions and to analyse their views on (and anticipation of) the selection criteria used by technology selectors. The interviews were complemented by participatory research during related conferences in the Netherlands.

The first interest in metals as hydrogen storage materials dates back to the 1960s. Researchers shifted their attention from electricity storage in metals (i.e. batteries) to storage of pure hydrogen. Nowadays this community is much larger and consists of researchers from different backgrounds such as chemistry and physics (both experimental and computational). Since 1999 the community has grown rapidly in the EU member states. For instance, in 2003 there were three ongoing EU research programmes, whereas in 2008 five networks existed (van Lente and Bakker 2010). The number of institutes involved in this research has increased as well. At the time of this case study six research groups were involved in metal hydrides research in the Netherlands which equals to roughly thirty researchers. These are located at the universities of Amsterdam, Leiden, Utrecht, Eindhoven, Delft, Twente and Nijmegen. All these institutes take part in the 'Sustainable Hydrogen' research program which is funded by the Dutch research council NWO. The program was an important factor in the growth of the Dutch branch of the hydrides community. Before the start of this program the community was limited to only two university groups. The other groups were dealing with comparable subjects and techniques, but never applied this to metal hydrides for hydrogen storage. During the formation of the research program, one of the communities' spokespersons was invited to suggest a number of research groups that could contribute to the goals set by the Dutch research council. Thereby he was given the chance to widen the community with research groups that did similar work, but never studied hydrogen storage materials. Since then, the community in the Netherlands has grown in terms of research groups, the number of scientists involved and the scope of research.

Early years

Since the start in the 1960s, researchers and car manufacturers have shown interest in metal hydrides as means of hydrogen storage and a number of different materials and approaches have been explored. The first hydrides under study were the so-called low-temperature hydrides. These relatively simple hydrides form when hydrogen atoms nestle interstitially in the metal's atomic lattice. The metals used for these hydrides were, among others, titanium, chromium and manganese (Buchner 1980). These hydrides can be used at low temperatures and are thus interesting for on-board applications as no temperature control system is necessary. Their main drawback is the weight of the base metals which results in a very heavy tank system. The weight of the tank system is detrimental to the performance of the vehicle and it is therefore the hydrogen-to-weight ratio of the system that has dominated the metal hydrides research heuristic: gravimetric density. It is often expressed as the weight percentage of hydrogen in the total weight of the system. For the low-temperature hydrides 2 wt% proved to be the maximum.

The next step came with the high-temperature, but relatively lightweight, metal hydrides. These metals, often magnesium alloys, have poor thermodynamics, but score excellent on gravimetric density. Theoretically these hydrides can contain up to 7,6 wt% of hydrogen. Unfortunately, these materials can only store hydrogen at temperatures above 200°C (Güther and Otto 1999). And this is not suitable for practical use because this would require active heating of the tank system and this lowers the overall energy efficiency of the storage system dramatically.

New hope

A new impulse to the community was generated in 1997 by Schwickardi & Bogdanovic through their article that demonstrated the high storage potential of alanates (for instance NaAlH4) when they are doped with TiO_2 (1997). The titanium oxide catalyst is able to lower the temperature range for ab- and desorption of hydrogen significantly. Their finding spurred new hope for metal hydrides. Research activities intensified significantly as can be seen from the number of articles in *International Journal of Hydrogen Energy* and the *Journal of Alloys and Compounds* (van Lente and Bakker 2010), two of the main outlets for the community. Together with the burst in alanates research, a large number of old as well as new hydrides were (once again) given a chance.

The three main characteristics by which the potential of metal hydrides is measured are the aforementioned gravimetric density, the operating temperature range and the kinetics of ab- and desorption. The rate of hydrogen absorption is seen as important because this determines the speed at which a consumer would be able to fill his car at the gas station. Therefore, a lot of effort was, and is, put into processing smaller particles of the most promising alloys. Small particles are desired because the rate of absorption is mainly determined by the length of the path the average hydrogen atom has to travel through its storage medium and also because smaller particles have a bigger surface area to weight ratio. Ball milling of the metals promises to produce ever smaller particles. The same goes for attempts to grow nanosized particles from watery solutions and so-called spark discharge formation. Other recent developments are the so-called MOFs, amides, imides and borohydrides.

Yet, so far no material has reached, under practical conditions, a higher gravimetric density than 3-4 wt%. This is considered to be too low. The US Department of Energy (DOE), for instance, has set a number a number of goals for hydrogen storage technology for the coming years. The weight percentage for 2010 should reach 6 wt% and the 2015 goal is 9 wt% (Department of Energy 2006, Department of Energy 2007). The goal for 2007 (4.5 wt%) was not reached. As said, no hydride material has been developed that scores well on gravimetric density, thermodynamics, and absorption kinetics. Likewise, the International Energy Agency and EU have set a number of goals for hydrogen storage systems (IEA 2004) but these are hardly ever mentioned as reference by the metal hydrides community.

To conclude this short history, metal hydrides have been on research agendas for forty years and expectations of further progress gave researchers their needed mandate. Even more so, the burst of research trajectories testifies to the unshaken belief in the future potential for metal hydrides. We conclude that it must have been expectations that convinced their sponsors because there are hardly any practical applications for metal hydrides yet. An exception should be made for some hydrides that are used for stationary purposes or in some niche markets like submarines (Hammerschmidt 2006). Still, the real promise of low-volume, energy efficient on-board storage has not come true so far.

Anticipating selection

This short history of metal hydrides research shows how the research community managed to survive by feeding and maintaining expectations. The expectations work of the community relates to their own technological option as well as to the competing options. For both, the community anticipates its future selection environment. It has an understanding of what its selectors desire and thus what its message should be. A key argument that the community has brought to the fore during the last decades is that both gaseous and liquid hydrogen storage are not, and will never be, satisfying solutions for the automotive industry. Thermodynamic laws, according to the prevailing arguments, prevent further development of these options in terms of storage capacity and energy efficiency. The metal hydrides community continuously points to these limitations and presents their option as the promising, but also challenging, alternative.

The promise of metal hydrides is constructed through a number of arguments. First and foremost, the progress that has been achieved is stressed. That is, even though metal hydrides do not meet most of the targets, some progress was made in terms of storage capacity and kinetics and an extrapolation of this progress is sometimes used by the community spokesperson to point out what further progress may lie ahead. Second, a better understanding of the underlying chemical and physical processes is seen as starting point for upgrading the materials' thermodynamics and kinetics. This goes especially for the group of alanates that is under study. And third, it is argued new alloys and catalysts, with higher capacities and faster kinetics, might be discovered as well.

The community stresses these points in their scientific publications, their contributions to conferences, and their negotiations with research councils. An often cited version of this argument is found in the Schlapbach & Züttel article in *Nature* (2001). Note, however, that the actual feeding of these grand expectations is done by a small number of formal and informal leaders in the community. Discussions like these, about the feasibility of metal hydrides as an alternative to liquid and gaseous storage, take place mostly at conferences and meetings where the wider hydrogen community is present. Only a few spokespersons are structurally involved in these debates.

Other members of the community are more likely to confine themselves to small scale expectations work in their research proposals and papers. These expectations relate to the outcomes of small research steps, rather than the wider potential of metal hydrides. According to the researchers, the claims are mostly qualitatively formulated such as: *'through better understanding of the underlying reaction mechanisms, we will be able to enhance the materials properties'*. The claims made in research proposals are almost never quantitative. One reason for this is that the scientists prefer to be prudent in their predictions in order to avoid disappointments on the selecting side:

"You will state in general terms that you want to destabilize the hydrides. Thereby you do not specify exactly what destabilizing is, that it occurs at eighty degrees or some specific pressure." (senior metal hydrides researcher)

The interviewees are not sure, however, how and when this disappointment could affect their mandate for further work. The focus of their expectations work concerns their specific research plans, while the promise of metal hydrides as such is not explicitly voiced but implicitly assumed. When they are asked to voice the expectations of their community they do this with the same modesty. Again, they do this to avoid disappointment and because they feel that many other actors are capable of judging the progress and potential of metal hydrides as well:

"You should have some ambitions, but you should not exaggerate. In a few years you will be held accountable and then you lose more than what you started with." (Senior metal hydrides researcher)

The small scale expectations work relates mostly to specific hydrides, catalysts, production methods, simulations, etc. Here the importance and potential of metal hydrides is taken for granted: what matters is that specific research is seen as promising within the field. Statements about the necessity of metal hydrides research, its promises, its competitors and the bigger issues such as the end of the fossil fuel era and the climate problem, clearly provide societal relevance for the research, but are less useful to promote the option of metal hydrides as such.

Selecting technologies

The promises and expectations that were voiced by the metal hydrides community are assessed and used by selecting actors. The selectors are more distributed than the enacting community. As metal hydrides for hydrogen storage are in the science stage of development, research councils and scientific program committees are the most prominent selectors. With support of their respective governments, they select promising research trajectories and the accompanying proposals. They do this by determining promising fields of research, by setting goals and targets, and by assessing results. Next to the research councils, car manufacturers also act as technology selectors: they select or reject technologies for further R&D work and eventually for use in their prototypes and future products.

Note that the distinction between enactors and selectors is analytically clear, but ontologically not straightforward, as actors that are selectors at one moment could act as enactors at another moment. For example, in the case of research councils it is hard to distinguish between enactors and selectors. Research councils are partly made up of scientists and those scientists are often part of the same community they have to select. The same goes for R&D efforts in industry: the company that enacts the technological solutions is selecting them as well: a firm that decides to use metal hydrides in its hydrogen prototype vehicles, will from there on claim that metal hydrides are a viable option that can deliver the desired performance to its future customers: it is then enacting metal hydrides towards the selectors of their promising options.

Enacting and selecting should therefore be seen as roles that actors play at a given moment. Yet, the distinction between the two sides of the quasi-evolutionary game is important analytically, to study and understand the processes that take place in the variation and selection of technologies. So we argue that it is possible to distinguish a number of selectors in relation to the technological options that are offered.

The selectors of hydrogen technologies and their assessments of the promises and expectations are most visible in the roadmaps and vision documents. Through these documents, the results of negotiations between governments, experts, and firms are communicated to the outside world, and a sketch is provided of the research that is thought to be necessary. To figure in these reports is thus vital to stay on research agendas and receive funding. The argument of the hydrides community, for example that gaseous and liquid hydrogen are fundamentally limited, is found in these documents as well. In fact, this negative argument seems more prominent than the positive argument in favour of metal hydrides and their future potential.

Since the Bogdanovic article in 1997, the selectors have granted the metal hydrides a wide mandate for further work. Members of the community have had no problems with getting funding for their research. The researchers enjoyed a great freedom in choosing their specific research aims and methods. This implies that the granted mandate, at least within the ACTS programme, is quite open. Whether this will last is rather disputed amongst the interviewees. Some believe that the peak of attention has passed and that, especially in the US, budgets will decline. Other interviewees feel that '*things have only just started*' and that funding will continue for the foreseeable future.

In the US, governmental research funding has risen over the last years and an even bigger share of hydrogen technologies R&D funding is requested by the DOE for (solid) materials for hydrogen storage (Department of Energy 2008). In the EU the picture is a bit different. Research funding for hydrogen storage solutions is continued in academic circles. However, it receives hardly any attention in the application (and demonstration) oriented Hydrogen Joint Technology Initiative (JTI) proposal for the period 2008 to 2015. In this public-private partnership the focus is on production, distribution and conversion (fuel cells) of hydrogen.

There are some signs that expectations of metal hydrides on the part of the selectors are indeed diminishing. This could very well be the result of disappointments about unfulfilled promises of further progress. One example of such disappointment can be found in an assessment report on EU funded hydrogen and fuel cells research The report critically reviewed the progress of solid hydrogen storage (including metal hydrides) and concluded that the performance is still far from the aspired targets (European Commission 2008). Both the EU and the US have defined targets for future on-board systems in consultation with the car industry to deliver the same performance, in terms of speed and range, as today's cars. The performance and progress of the different storage options are assessed against these targets and the options are expected to meet different targets at different points in time. In practice, it is likely that none of the known storage systems will meet these targets and therefore the metal hydrides community compares itself with today's leading option, 700 bar high-pressure gaseous storage. The interviewed researchers acknowledge that metal hydrides at this stage cannot meet the performance of the high-pressure tanks, and they are also hesitant about the targets set by the DOE, EU and IEA. While they sometimes use these targets to stress the need for further research, they do not agree with them in terms of the actual needs of the car industry. From their contacts with the industry they figure that a weight percentage of 5% would be enough, provided the system meets other conditions in terms of operating temperatures and fuelling times. Especially the DOE norms are considered to be not realistic and driven by current car design and performance (i.e. SUV's) rather than accepting a different mode of personal transport that would require less hydrogen on board for an acceptable driving range.

2.5 Conclusions: Arenas of Expectations

In our case study we have witnessed what types of expectations the metal hydrides community has constructed and how they conveyed these to its selectors. This enacting community has put to the fore why metal hydrides are promising, and why the competing solutions are not promising. We have also witnessed how the selectors responded to these expectations and what mandate was given to the hydrides community to continue its research. In this section we place our findings in a generalized framework for the role of expectations in the variation and selection of emerging technologies: *arenas of expectations*.

As outlined in the introduction, technological communities of enactors and their expectations are in competition with each other for funding and other forms of support. They fight their battles on battlegrounds we propose to call *arenas of expectations.* These arenas can be defined as the loci where expectations are voiced by the enactors and tested by the selectors, where they are confronted with experience, knowledge, and interests. The important point is that ongoing processes of variation and selection of emerging technologies are not just bilateral interactions but a collective social process over time, engaging a lot of different, competing, actors and organizations. These multi-actor interactions take place at scientific conferences and journals, in the wider media, committees, research councils, and so forth. Within arenas of expectations 'trials of strength' (Latour 1987) take place between the circulating expectations of the different options. An important part of these trials is based on earlier experiences, for instance in the case of failed promises such as we have witnessed in our case study. The expectations are confronted with facts and forces of the social and economical context in which they are supposed to become realties. Therefore, the accumulation of knowledge and failures, expectations and disappointments, hopes and fears become relevant in arenas. It is in the arenas that the cultural matrix of expectations, as proposed in the quasi-evolutionary model of technology development, is given further shape and content. In Figure 2.2 we summarize how, in the arenas, the expectations work of the enactors and selectors meets.

It shows, on the left side, that enactors feed and maintain expectations in the arena. They have to do this in order to receive a mandate for further work on improving their technology. This mandate is granted when technology selectors are convinced of the future potential of the technology, that is, for the time being. At stake, thus, is the robustness of the expectations in the arenas: too much contestation harms the mandate for the enacting community. The drawback of robust expectations, however, is that they may constrain the enactor community not to deviate from their promising approach.

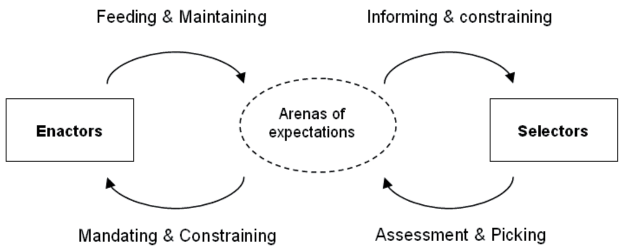

Figure 2.2 Arenas of Expectations

Selectors inform (and also constrain) themselves with expectations, they make assessments and pick their winners. As a result, some variations are favoured or at least not too strongly contested by selectors: others are seen as not viable, or as not yet viable. The outcomes of the selectors' decision making process feed back into the arenas and influence the ongoing struggle for mandate. How and why exactly the selectors come to their assessments of the different expectations in the arenas is a question that we think deserves further study. The multitude of options for each of the elements in the prospective chain of hydrogen technologies is testament to the fact that technology selectors maintain a portfolio of options that are given a chance to develop further. Such portfolio approaches are common, but it is not fully understood why some options are thought to be credible and others are not.

From the case study we conclude that multiple arenas may co-exist at various levels of aggregation. Highly detailed expectations of materials or techniques are tested in different arenas than, say, expectations about the hydrogen energy system as a whole. Specific expectations will circulate in specialized scientific committees, where the merits of the 'hydrogen economy' figure in public debates on sustainable energy. Nonetheless, high expectations of a specific hydride alloy may find their way into the vision level arena as well. Be it that in the latter arena it is mostly the community spokespersons that have their say.

In order to study the enaction and selection process in the case of hydrogen storage technologies, we analyzed the expectations work, the act of feeding and maintaining expectations, performed by the technological community that tries to develop metal hydrides for hydrogen storage.
In Figure 2.3 we have summarized expectations and statements that appear in the hydrogen storage arena of expectations. The short statements in the figure highlight the success of the metal hydrides community in convincing the selectors of their solution's potential for the hydrogen chain of technologies. It has granted them a place in the hydrogen chain and on research agendas, notwithstanding doubts about the cycleability and cost (the search is mostly about finding a lightweight, high capacity hydride).

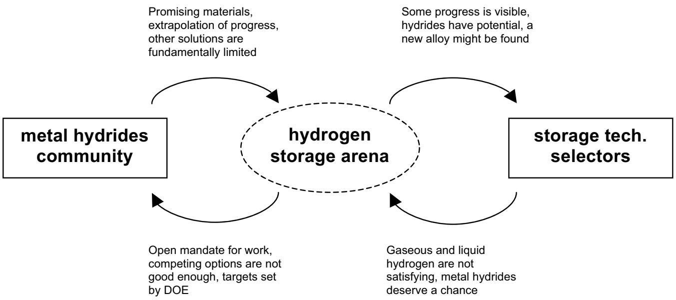

Figure 2.3: The expectations work in the hydrogen storage arena

Expectations about the other storage methods are clearly negative within the metal hydrides community: they will not improve significantly and are unfit to support a sustainable hydrogen energy system. Within the wider hydrogen community, a lot of actors, certainly in the car industry, are working on further improvement of gaseous storage and the boundaries are pushed beyond 700 bar. The energy losses involved are apparently acceptable in this phase and it seems that car manufacturers might accept lower specifications than the goals set by the DOE.
Surely, metal hydrides researchers support hydrogen as energy carrier and quite often mention the need for a replacement of fossil fuels because of the climate issue and the depletion of supplies. For them, the role of metal hydrides is crucial, while this does not seem the case for actors in the wider hydrogen arena. The wider hydrogen community, including its selectors, regards on-board storage as highly important, but the development of metal hydrides is not vital to the future of hydrogen. Still, metal hydrides provide a useful promise to silence the critics of hydrogen as fuel of the future. That is, the very fact that there is an option for on-board storage that holds the promise of solving the storage problem in the future, makes the prospective chain of hydrogen technologies a bit more credible.
To conclude, the exchange or communication of expectations does not only take place in bilateral and synchronous fashion during bridging events as proposed by Garud and Ahlstrom (Garud and Rappa 1994), but also in a more multilateral and asynchronous fashion through scientific articles, foresight activities, roadmaps, funding decisions, etc. The actors and their expectations and promises meet in different arenas of expectations for different aspects of the technology and for different levels within

the prospective technological system. The interaction between enactors and selectors in the arenas of expectations results in the coordination of research activities, the selection of technologies and their further development for market introduction. Arenas of expectations, therefore, provide an important link between the processes of variation and selection.

3. Expectations work of hydrides researchers

3.1 Introduction[7]

Transformations in energy systems are complex and uncertain processes in which competing technical options abound. Traditional arrangements are questioned and various new ones are brought to the fore as important future solutions. While the carbon based energy regimes are under stress, visions about new energy sources and infrastructures abound. They circulate among national bodies, such as the US Department of Energy and supranational bodies, such as the EU, and many other actors in the energy system. One of the observations to be made here is that the various technical options compete in terms of their performance and in terms of expectations about future performance. The relevance and significance of a technical option is thus defined by both assessments of its current characteristics as well by assessments of its potential future performance. This article is based on this observation and seeks to explore the consequences.

Competition between technologies is a well-known phenomenon. In the theories and models of competing technologies as developed by Brian Arthur (1989), James Utterback (1994) and others, competition is based on actual technical performance. We will argue that technologies in their very early stages will compete with alternatives on the basis of expectations and promises of future progress. As a result, the promises of future specifications will be pertinent and carefully maintained.

In this paper we focus on the competition between three technologies that figure in visions of the 'hydrogen economy', three technologies that promise to solve the on-board storage of hydrogen in vehicles: as a gas, as a liquid or in metal hydrides, respectively. In general, the history of hydrogen

7 This chapter is published as: van Lente, H. & Bakker, S. (2010) Competing expectations: the case of hydrogen storage technologies, *Technology Analysis & Strategic Management*, vol.22, no.6, 693-709

technologies is characterised by a number of particular research and development lines, in combination with promises and broad visions about hydrogen economies and hydrogen societies. These promising technologies, however, have to compete among each other (and with established technologies) in terms of visibility and credibility. None of the three on-board storage technologies of hydrogen are currently seen as fulfilling all the prospective needs of a hydrogen economy. Their current technical performance and cost attractiveness, in prototypes or laboratories, are seen as insufficient and the competition has shifted to expectations about future performance.

We will proceed as follows. In the next section we will review the two central perspectives of this article: the dynamics of expectations and the competition between technological options. Then we will explore the hydrogen visions and the sequence of steps they invoke: production of hydrogen, distribution, storage and use (Section 3.3). This chain of hydrogen technologies is not fully in place yet, but for each steps various options have been suggested. To trace the competition between technologies in one of the steps, storage, we examined 263 articles on 'hydrogen' and 'storage' that have appeared in scientific and engineering journals, from 1975 until 2005. In the analysis of claims we use the model of argumentation developed by Stephen Toulmin (1958), who distinguishes between claims, data, warrants, backings, rebuttals and qualifiers in an argumentation. The analysis of the number and content of claims in the articles highlights historical patterns in the competition of the three technologies (Section 3.4). We conclude with a reflection on the nature of the competition and suggest an additional, 'expectation' phase to the framework of competing technologies.

3.2 Expectations and competition in technical change

Expectations are of great importance for the development of technologies as they stimulate, steer and coordinate action of actors (Borup et al 2006). The concept of expectations as key driver for current technological change was introduced by Van Lente (van Lente 1993), and has been developed into a 'sociology of expectations' (van Lente 2000, Brown et al. 2000). The basic idea is that expectations, because of their content, are able to coordinate action, and, in this way, to shape developments in science and technology. Expectations - and promises, which are positive expectations - can be defined as statements about the future that circulate; they contain a script, that is, a description of the future situation and a concomitant distribution of roles for selves, others and technologies (van Lente and Rip 1998b). When expectations are shared they can be used as a resource to legitimise action and as heuristics to guide decisions. Moreover, promises and expectations of technology are part of the agenda setting processes in research groups, firms or governments (Guice 1999). Agendas, by definition, are lists of priorities, that is, items that require action (Kingdon 1984). What started as a promising option may then be translated into a required action: into a technical specification to be met and into a distribution of tasks. That is, the promise has turned into a requirement. Van Lente (1993, 2000) coined the notion of a 'promise-requirement cycle' as a basic mechanism (see Figure 3.1). For instance, when the fuel cell is seen as a promising option that in 10 years time may compete with the internal combustion engine (in terms of mileage, speed, safety and costs), and when because of this promise the development of fuel cells has become part of research, firm and governmental agendas, the researchers, firms and governments are expected to deliver within 10 years a fuel cell that competes with the internal combustion engine. The promise of the fuel cell has been transformed into the requirement of the fuel cell in terms of mileage, speed, safety and costs. One of the important aspects of the promise-requirement cycle is that niches or protected spaces are created, in which attempts to fulfil the promise are protected. Attempts are seldom immediately successful and their failures need a suspension of selection. Niches may be effective at the level of individual firms where projects need protection, at the level of techno-scientific fields where research themes compete or at the societal level of generic cultural orientations, where technological progress as such is defended against other orientations. Protected activities within niches will lead to other, often more specific expectations that, in their turn, may result in new requirements. This multi-level and nested character is described in Table 3.1. As a rule, technical change is embedded in complex structures of expectations: specific expectations about, say, a new polymer to be used in fuel cells, are considered as important because they relate to the general functional promise of fuel cells research, which, in its turn, is related to the generic outlook of new, alternative forms of energy production and consumption. For all levels, specific actors and spokespersons will compete and be active in 'expectations work': raising, maintaining and controlling expectations.

Promises, thus, are mixed blessing. On the one hand, they raise resources and protection, on the other hand, they return as obligations. The combination of a freedom to operate on the one hand and an obligation to deliver has been characterised as the mandate for engineers and other actors (van Lente 2000). This mandate, in terms of funding and other forms of credit, provides the opportunity to continue the development of a technology. A mandate also comes with requirements that should be met: again expectations and promises lead to requirements. Note that coordination of action occurs when expectations interlock at different levels of technology development (Borup et al 2006). As a consequence, what starts as a discursive reality may end up as a technical reality (van Lente and Rip 1998b), and this aspect pervades the process of technical changes, in particular under conditions of uncertainty.

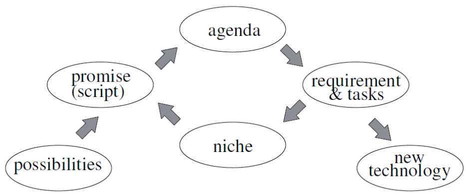

Figure 3.1 Promise requirement cycle (Van Lente, 1993)

Table 3.1: Levels of expectations

	specific	functional	generic
builds on and adds to	local agenda (of a firm or research lab)	agenda of a technical-scientific field	societal agenda
leading to	technical requirement	functional requirement	protected space (niche)
character	articulates a specific technical possibility; quantitative; 'material X will meet criterion Y in two years'	highlights a range of functions; qualitative; 'materials like X will have good electric properties'	sketch of encompassing future; general; 'new materials like X will change the economy'
fallibility	high	medium	low

The sociology of expectations has described in some detail the constitutive role of expectations in science and technology. Often, however, expectations have to compete in order to remain forceful. This aspect has received much less attention and therefore we introduce a second approach to guide our search for competing expectations: the dynamics of competing technologies. In general, competition between rival technologies is an important theme in the study of technology and innovation. The work of Brian Arthur on 'lock in' (1989) and Abernathy and Utterback (1978) on industrial change address the dynamics of competing technologies in terms of innovations, markets and industrial structure. The three phase model developed by James Utterback (1994) is a useful summary of the insights gained in this research tradition. A central idea is that the competition takes place in different phases, respectively the fluid, transitional and the specific phase (see Figure 3.2). While the notion of phases introduces a sense of linearity, note that the model includes re-interpretations, learning processes and feedback mechanisms. In the fluid phase, which may take decades, many firms enter the market with competing models and designs. The competition is in terms of the characteristics of these models and designs, and much less on the basis of quality and cost. In this first phase many product innovations take place and less process innovation. The central process here is the learning between developers and users: what are the important characteristics of the technology and what should count as a good model? In the transitional phase a so-called dominant design emerges and the amount of technological variety decreases. The number of competing firms also decreases. In this phase, process innovation becomes much more important, while product innovation becomes less distinctive. The nature of competition shifts from model specifications to costs and quality. In the specific phase, the competition has fully shifted to cost and the number of producers has dropped to an oligopoly. The focus of innovative activities is on process innovation. Only minor, incremental, changes are made within the dominant design. The phases are summarised in Table 3.2.

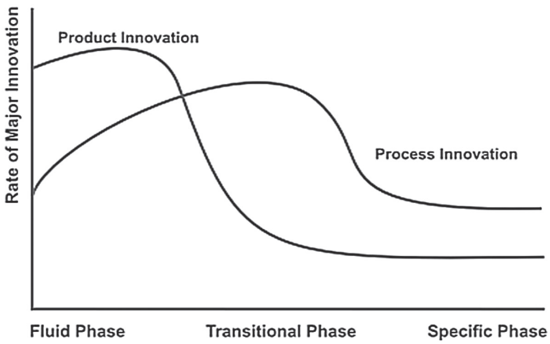

Figure 3.2: Three phases of the Utterback model

To locate hydrogen technologies in this scheme is difficult, since there are hardly any products on the market, and the products and systems that are currently sold seldom relate to the encompassing visions about a 'hydrogen economy' or 'hydrogen society'. Yet, competition takes place, but the technologies compete with alternatives on the basis of expectations and promises of future progress.

Table 3.2: Three phases of competing technologies (based on Utterback 1994)

	Fluid Phase	Transitional Phase	Specific Phase
Product	High variety	Dominant design	Incremental innovation
Process	Flexible and inefficient	More rigid	Rigid and efficient
Organization	Informal and entrepreneurial	Project- and task groups	Mechanistic
Market	Fragmented and unstable	Stabilizing	Homogeneous
Competition	Many small firms, broad variety	Intensifying with more similar products	Oligopoly and similar products
Basis of Competition	Functional product performance	Fitness for use	Price and quality

How to describe and locate the competition of hydrogen promises? While the perspective of the 'sociology of expectations' focuses primarily on new, emerging technologies, the perspective of competing technologies tend to focus on more developed technologies. A conceptual possibility is to assume a phase that is earlier than the fluid phase, in which in which technological varieties compete before market factors come into play. In this so-called 'expectation'-phase competition must be based on something else than product features and price, because neither the technology, nor the market or the users can be said to exist. Instead, the competition between the technological varieties is based on expectations of future developments in terms of characteristics, performance and price.

In this paper we will explore the expectation phase and highlight one particular competition: the rival solutions to on-board storage of hydrogen. Basically, there are three storage options: gas, liquid and metal hydrides. While car manufacturers are working on the commercialisation of hydrogen vehicles and policy programmes support hydrogen as an energy carrier, the future of a 'hydrogen economy' is still uncertain. In the midst of this uncertainty, numerous technologies are being developed for hydrogen fuelled vehicles to support the concomitant hydrogen energy systems. To compress or liquefy gas is an option, but storing enough hydrogen on-board a vehicle is problematic given the low (volumetric) energy density of hydrogen in its gaseous state and the high energy loss when stored in a liquid state. Yet, metal hydrides researchers, in their turn, have not found what they are looking for. They can continue their work as long as their sponsors have high enough expectations of their quest for better alloys and catalysts. In the next section we will have a closer look at the setting of this competition. In Section 3.4 we will analyse the specificities of the competition between the three storage options.

3.3 The Prospective Chain of Hydrogen

In hydrogen vision reports (Department of Energy 2002, Duwe 2003, HFP 2005, European Commission 2006, Marshall 2006, Vermeulen 2006) a number of differing 'visions', or, in our terminology, generic expectations are presented (McDowall and Eames 2006). These visions mainly aim at mobilising support for hydrogen technologies on the whole. This support is much needed because hydrogen is not the only contender in the race for the future of energy. For mobile applications, for instance, hydrogen faces competition from, among others, bio fuels and various types of batteries. Because so much is uncertain about the future of energy production and consumption, the hydrogen visions tend to be rather open and ill-defined in terms of specific technological solutions and modes of use. This leaves room for interpretation and for competition between different specific expectations. So, hydrogen proponents, on the one hand, compete with other hydrogen technologies; on the other, they will seek to convince outsiders of the future possibilities of hydrogen in general. They can claim or colonize (Brown and Michael 2003) their share in the future of transportation energy systems and use all kinds of arguments to support hydrogen and to build on a number of positive images of hydrogen technologies (Eames et al 2006). To make the generic hydrogen vision(s) credible, proponents and other interested actors need to show the technological possibilities of a hydrogen energy system.

Commonly, the hydrogen energy system is divided info four main elements: production, distribution, storage and end-use. For all of these parts there is a number of enabling technologies and approaches that are contestants to fulfil the systems' needs (Murmann and Frenken 2006). Currently, none of these technologies is 'ready' to function without further development, adaptation or testing. They are either too expensive, are not efficient enough or have not proven to work at all. The configuration of these elements of the hydrogen vision is what we define as the prospective chain of hydrogen technologies (Figure 3.3). It is not a representation of an existing chain, but a projection of things that could come into being. In all hydrogen visions this prospective chain or a variety of it, is used explicitly or implicitly, and is filled in with promising technologies. While most of these technologies do not perform as envisioned, hydrogen visions bring them together in a narrative of future production and use. Note the interdependencies of expectations at various levels: the credibility of the generic expectation of hydrogen as an energy carrier is built upon the functional and specific expectations of the constituent elements of the chain, while these, in their turn, refer to the encompassing vision. Hydrogen visionaries and other proponents of the generic expectations need to create and maintain expectations of specific component technologies when they defend a hydrogen energy system or even a 'hydrogen economy'. We will briefly investigate the prospective chain and the options for on-board storage of hydrogen.

Hydrogen, regularly produced in its gaseous state, has a very low energy density (energy per volume). This means that one would have to store very large volumes of the gas to provide a hydrogen vehicle with a drive range that is comparable to a gasoline car. To illustrate the issue, a vehicle typically requires 4-8 kg hydrogen to drive 400 km, which is little in terms of weight compared to gasoline. However, under atmospheric pressure, 4 kg of hydrogen occupies 45 cubic meters. Something has to be done to store the hydrogen in a more efficient manner. There are three basic options to achieve lower volumes: high pressure gas, liquid hydrogen and storage in solid materials. We discuss these options in the following paragraphs, based on an analysis of the roadmaps and scenario studies mentioned above.

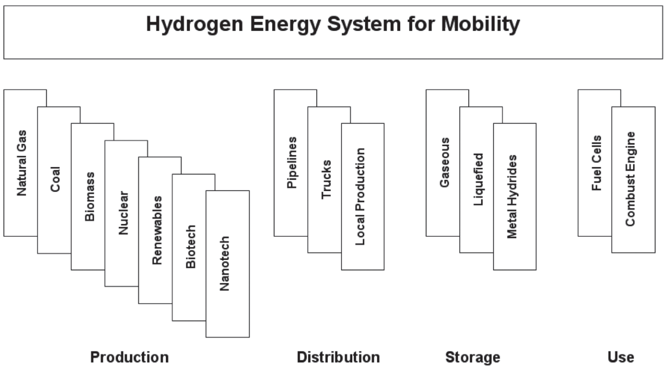

Figure 3.3: The prospective chain of hydrogen technology options

Storing gaseous hydrogen under high pressure is seen as the least complicated option. But the pressures needed in order to reduce the volume enough are enormous and that raises a number of problems, such as safety, price, and energy efficiency. The development of hydrogen pressure tanks mainly focuses on high-strength/low-weight materials. The first hydrogen gas tanks in the 1980s were filled up to 200 bar. However, an acceptable drive range would require bigger tanks than 200 litres (Schlapbach and Zuttel 2001, Das 1996). New materials allow the construction of 350 and even 700 bar tanks made with carbon fibres and epoxy resin. The 350 and 700 bar tanks can now be considered as standards, used in hydrogen filling stations and have been approved for use. Compressing the hydrogen up to these pressures requires a lot of energy, leading to energy losses up to 20%.

The main advantage of the liquid hydrogen option is the much higher density, about double the density of 700 bar gaseous hydrogen. But energy losses are even bigger when hydrogen is liquefied, up to 30%. This is because hydrogen has to be cooled to - 252 °C. And with such extremely low temperatures, the tank system requires an insulation which adds to the total weight and volume. Furthermore, some hydrogen will evaporate and it has to be released as this so-called boil-off would otherwise build up too much pressure in the system. Releasing hydrogen is not only a loss of efficiency: it could also create safety risks when the car is in an enclosed environment.

A less obvious, but interesting, method is to store hydrogen in solid materials such as metal alloys. Some metals, when exposed to hydrogen, form metal hydrides in which the hydrogen atoms are stored in the atomic lattice of the metal. A typical metal hydride has a higher density, in terms of volume, than gaseous and even liquid hydrogen. Since metals are not among the lightest materials, the gravimetric (weight) density is much less: typical weight ratios of hydrogen in metal hydrides are around 2–3% (expressed as weight percentage: wt%). Storing enough hydrogen to allow an acceptable drive range would require a far too heavy storage system. The biggest challenge, therefore, is to raise the gravimetric density. Researchers are looking for alloys with a higher hydrogen content. Some metal and alloys are theoretically capable of storing up to 15% hydrogen. Yet, there are some other issues to be dealt with. The hydrogen should not only be absorbed by the metal to form a metal hydride, it should also be released when the hydrogen is needed for the vehicle. The absorption reaction is exothermic (heat is released by the system), and desorption is endothermic (heat has to be added to the system). The temperatures needed to release the hydrogen can be anywhere between room temperature and 300°C, depending on the alloy. So far no alloy has been found that can reach the high gravimetric densities needed and at the same time operate at feasible temperatures when releasing the hydrogen. It is often proposed that the required heat should be taken from the fuel cell – another element in the prospective chain – as this would limit the operating temperature to about 80°C. Further issues with metal hydrides are among others the kinetics (as fuelling time is dependent of the rate of absorption), and the ab- and desorption cycles.

In 40 years of metal hydrides research three main groups of materials have been studied. Low-temperature hydrides were the first materials that put metal hydrides on research agendas of hydrogen storage (Schlapbach and Zuttel 2001). Low-temperature hydrides are relatively simple metals or alloys, like titanium iron (TiFe). The operation temperatures are between 80 and 150 °C. The downside is that they can only store 2 wt% hydrogen, too little to be practical for mobile applications. High-temperature hydrides can achieve gravimetric densities up to 7.7 wt%. Magnesium, a lightweight metal, is most often used metal in high-temperature hydrides. Its operating temperature is 300 °C is unpractical for mobile use and the desorption kinetics are slow. To solve these issues a lot of experiments have been conducted with more complex alloys and with potential catalysts, but both operating temperature and kinetics have so far not reached a desired level. Another research strand aims to increase the specific surface area and other physical properties of the materials, to enhance the kinetics. The third group

of materials are alanates, these are lightweight aluminium based materials, such as sodium ($NaAlH4$) and lithium ($LiAlH4$) alanates that can also be used as hydrogen storage medium.
Densities up to 5.9 wt% can be reached with alanates. Again however, operating temperatures are too high for practical use (200-300 °C). The ab- and desorption kinetics are also not at the level to fit with the overarching hydrogen promise. Besides these three main options, a number of less prominent storage methods are studied. Much attention was given to carbon nanostructures that were said to store more than 50 wt% of hydrogen, by means of adsorption rather than absorption, but this result was seldom achieved. Chemical hydrides, bonding hydrogen to a liquid chemical substance, is also one of the options under study. Since the turn of the millennium, borohydrides and clathrates have received considerable interest.

To sum up, none of the storage methods has the desired properties for mobile use. Volumetric and gravimetric densities, energy efficiency, drive range and refuelling times do not meet the requirements that of the roadmaps and scenario studies that underpin the prospective chain. The functional expectation that hydrogen can be stored in a safe and cost-effective way is filled in with three options that compete against a background of common targets. The most prominent targets are formulated by the US Department of Energy (DOE) in the FreedomCAR project, and include requirements for volumetric and gravimetric density, operating temperature range, costs, cycle life, etcetera. These targets are widely used as benchmark for future specifications, also in EU and IEA projects. The clearest target for the metal hydrides community is the gravimetric density. This is set at 6 wt% for 2010 and 9 wt% to be achieved by 2015.

To illustrate which groups are involved in the activities to meet the requirements and thus which functional expectations dominate, we have gathered data on research networks in the EU: data are available for the period 1999-2008. An analysis of the EU Framework Programmes was combined with a systematic online search to find information on the networks, their timeframe, the organisations involved, and specific research topics. Table 3.3 presents an overview of the research networks in the EU. Most of these deal with metal hydrides and some are also concerned with carbon nanostructures. The first network diagram shows the situation in 2002 (Figure 3.4). In that year three research networks were working on hydrogen storage. The second diagram shows the situation for 2008 (Figure 3.5). It illustrates the increase in the number of organisations working on hydrogen storage research. Again, most of the research concerns metal hydrides research. The groups focussing on carbon nanostructures – a new promise - are part of these networks as well. Gaseous and liquid storage receive less attention in academic research and is mainly concerned with new materials for the construction of hydrogen tanks.

Table 3.3: EU hydrogen storage research networks

Research Network	Period	Topics
Fuchsia	2001-2004	MH
Hystory	2002-2005	MH
Hymosses	2002-2005	MH, carbon nanostructures
Sysaf	2003-2006	implementation, safety and standardization
Storhy	2004-2008	G, L, MH
Hytrain	2005-2008	MH, carbon nanostructures
Hycones	2006-2009	carbon nanostructures
Hydrogen	2006-2009	MH
Cosy	2006-2010	MH
Nesshy	2006-2010	MH
Hysic	2007-2008	supportive research
Nanohy	2008- 2011	nanostructures

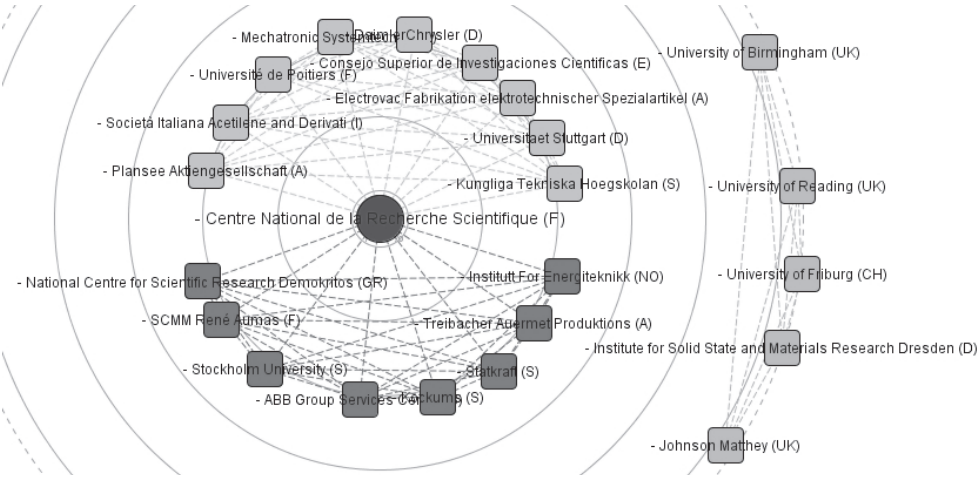

Figure 3.4: hydrogen storage research 2002

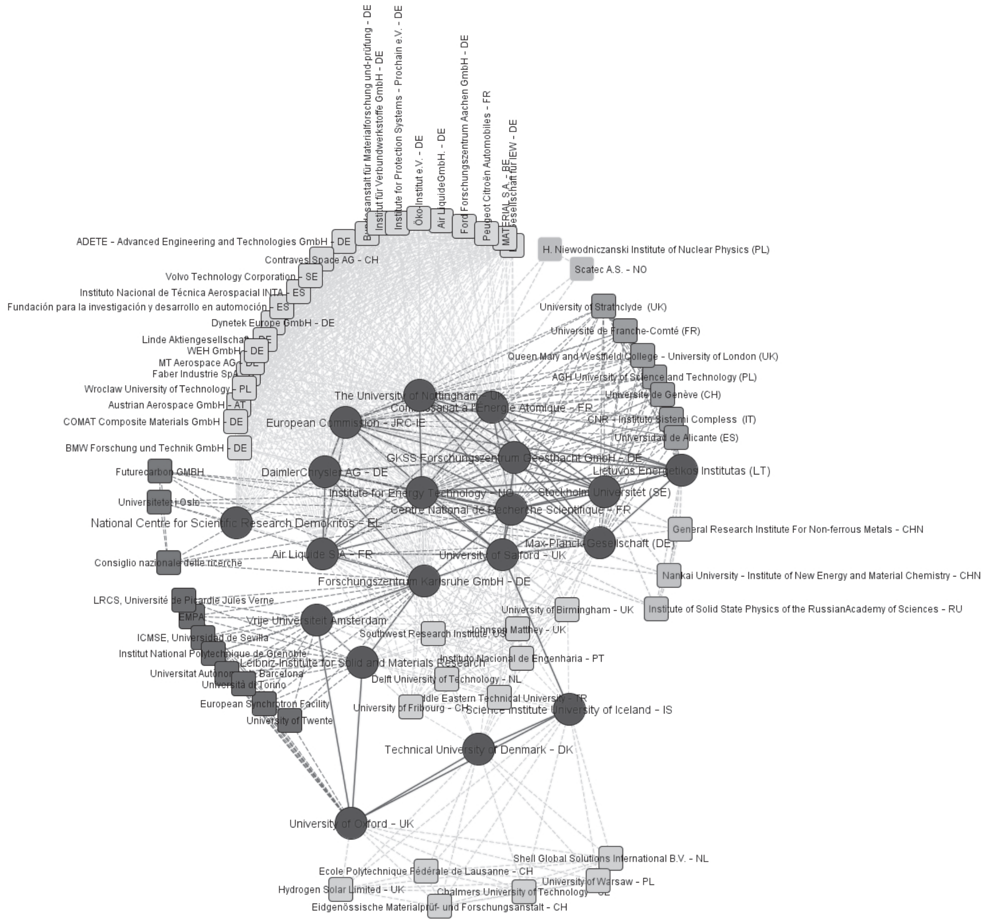

Figure 3.5: hydrogen storage research 2008

3.4 How to store a promise

In this paper we address the question how promising technological options compete. We have seen how the three options for hydrogen storage - liquid, gaseous and in metal hydrides - and are given a position in a prospective hydrogen chain. We will now further analyse the competition of expectations in scientific journals, where hydrogen storage technologies figure as prospective entities. The expectations of the various storage options are corroborated or contested in the four main journals in which the claims on storage options appear: the *International Journal of Hydrogen Energy*, the *Journal of Power Source*, the *Journal of Physical Chemistry*, and the *Journal of Alloys and Compounds*, until 1991 known as the *Journal of the Less-Common Metals*. The first two journals have their focus on hydrogen and energy in general and, as a rule, contain rather application oriented articles. The latter two are more science oriented and claims are phrased as basic scientific findings. We assume that this combination of journals provides a sensible overview of the competition between technologies of the (far) future.

In general, expectations can be defined as circulating statements (Borup et al 2006, van Lente 2000) that derive their force from the linkages that are made between actors, artefacts and activities. How to trace the linkages and the shift in linkages? A useful generic scheme for the analysis of claims and argumentation was developed by Stephen Toulmin (1958). The scheme has been used in many contexts, including scientific argumentation (Weinstein 1990), and can be used for our purposes as well. Toulmin's scheme consists of six elements: claim, data, warrant, backing, qualifier and rebuttal. See Figure 3.6 and Table 3.4.

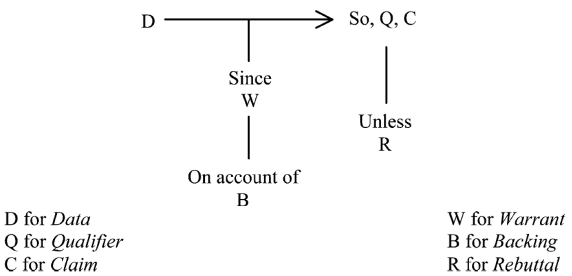

Figure 3.6: General lay-out of the Toulmin scheme (from Verheij 2005)

In any argumentation, the *claim* is the most important element, the central message of the argument. A claim is primarily based on *data,* of whatever type, and a claim will be stronger when there is more supportive data. The logical connection between data and the claim is made by the *warrant*. Toulmin distinguishes three types of warrants. The first is the *authoritative warrant*, when it is backed by experts that are authoritative in the given setting. The second is the *motivational warrant*, referring to norms or values presumably held by the targeted audience. The third is the *substantive warrant*, which suggests a basic causal relation. As warrants may not always directly convincing, a *backing* is sometimes added to strengthen the warrant and thereby the claim. An extra means of supporting the claim is the *qualifier*: information or conclusions from other settings or debates. Moreover, limitations and weaknesses of the argument can be protected by a *rebuttal*, which addresses counterarguments before they are voiced by the opposition.

We haven taken relevant articles from 1976 onwards (the year that the IJHE was launched) up to and including 2005. Articles were selected with the keywords 'hydrogen' and 'storage' in the article title. Within this set of 665 articles, a further selection for a closer study was made to articles that contain a claim about the options to store of hydrogen, for instance 'for on-board storage of hydrogen, metal hydrides are the best solution'. Table 3.5 shows the number of articles in our data set, as well as number after the second selection, in total 263. The argumentation in the selected articles was analysed through coding text fragments to identify data, warrants, backings, qualifiers, and rebuttals.

We also noted whether these fragments are used to support the claim or to weaken competing options. These data were then organised in a database which allows a longitudinal analysis. We will discuss the historical trends, as well as the nature of the competition that is revealed in this way.

Table 3.4: elements of the Toulmin scheme

Claim	**Claims made about the solution under study in the article. Both negative and positive.**
Data	**The data leading to the claim, such as storage capacities, operating temperature, etcetera.**
Warrant	**The bridge(s) between data and claim. Three types:** **Motivational, what we all 'agree' on** **Authoritative, what experts 'agree' on** **Substantive, building on basic cause and effect relations**
Backing	**Remarks supportive to the warrant(s), often a description of future technological requirements**
Rebuttal	**Weaknesses of the claim as voiced by the author.**
Qualifier	**Remarks that support the claim, but taken from wider debates. Both about the own solution, but also (negative) about other solutions.**

Table 3.5: Overview of articles in our database

Journal	Articles with 'hydrogen' and 'storage'	Articles with claim on metal hydrides	Journal impact factor 2006
IHJE	**225**	**103**	**2.615**
JPS	**43**	**12**	**4.115**
JAC	**380**	**134**	**1.250**
JPC	**17**	**14**	**3.521**

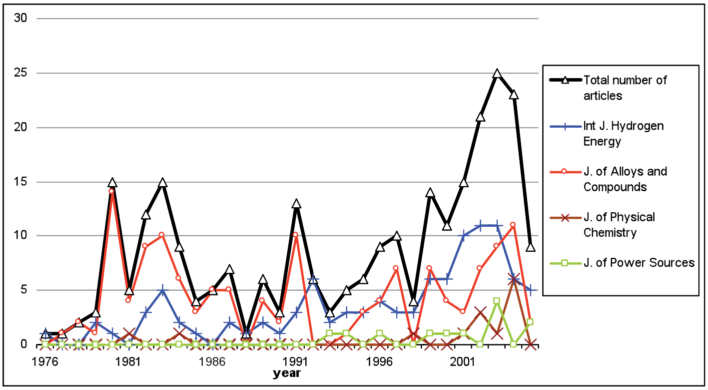

Figure 3.7: Articles in our database from the four journals

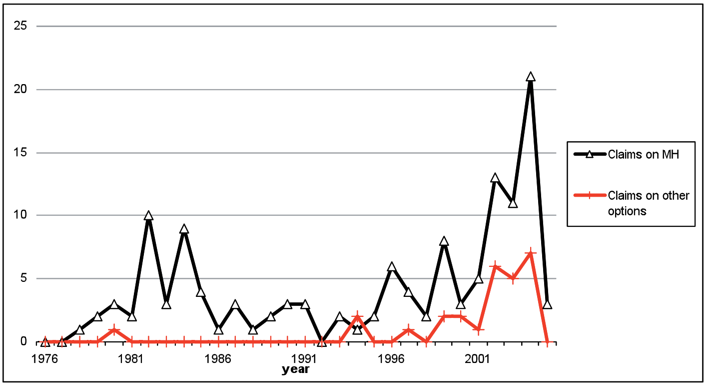

Figure 3.8: The number of claims made throughout the years

The number of articles published per year on metal hydrides suggests three periods of research on hydrogen storage. Figure 3.7 shows a peak in the early 1980s, less activity in the 1990s and second peak in the early 2000s. These periods confirm the narratives of four central review articles, Buchner (1980), Peschka (1987), Guther and Otto (1999) and Chandra (2006) The 1980s, then, are seen as the first period of interest in metal hydrides, with research on low-temperature metal hydrides and the introduction of high-temperature hydrides. In the second period, 1990-1997, there is less research and results are not inspiring. Between 1987 and 1999 there has been no review article from the community, this confirms the sense of stagnation of research in that period. Guther and Otto (1999) stress that only after the 1997 article by Bogdanovic the field got a new impulse. In this article, Bogdanovic and his co-workers describe the results of doping alanates with titanium, which lowers the desorption temperature from 300 to 200 °C. This result was received as an expectation that much more could be achieved by adding catalysts. The third period, starting with the 1997 Bogdanovic article, shows renewed interest in metal hydrides with many different research strands.

In the *first period*, from 1976 to 1990, the first ideas about a 'hydrogen economy' were published and debated and led to requirements for hydrogen storage. The generic promise of the hydrogen economy was unarticulated and the benchmark for specific expectations in that period was the gasoline tank. Scientists were aiming at storing the same amount of energy in a hydrogen vehicle (Peschka 1987). We identified an increase in claims supporting metal hydrides, starting from 1982. After 1985 the number of claims decreased again and remained low for 10 years, see Figure 3.8.

Warrants indicate the relevance and veracity of the claims research done, as stated by the scientists themselves. In Figure 3.9 we show the number of warrants in articles and the three types of warrants distinguished above: substantive, motivational and authoritative. There is no clear pattern here, apart from the same trends as noted above. Typical warrants used throughout the years refer to the hydrogen economy:

"In the future hydrogen will probably play an important economic role as a raw material and eventually as an energy carrier. One major aspect of such a development seems to be storage facilities." (Pezat et al 1980)

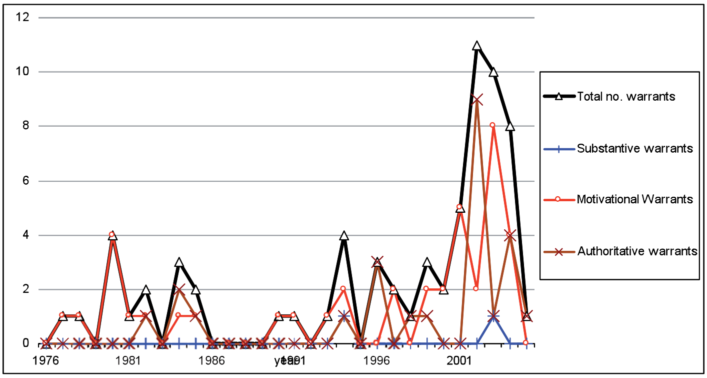

Figure 3.9: The number of warrants used throughout the years

According to the review articles no significant breakthroughs occurred during the *second period*, 1990-1997. The research on metal hydrides focuses on experiments with different alloys and different ratios of the metals used. Gaseous and liquid storage are seen as competitors, but these are said to be incapable of solving the storage problem. According to review articles, the field of hydrogen storage research was in a period of stagnation. The absolute number of claims made in this period was lower than in the previous period, but the warrants do not change in tone. The number of warrants increased somewhat, but not significantly.

The *third period* starts with an increase in the number of articles, which, according to Guther and Otto (1999) and Chandra (2006) were the result of the introduction of alanates in the field. In his 1997 article Bogdanovic demonstrated the positive catalytic effect of doping an alanate with titanium. This lowered the temperature of desorption of hydrogen from the hydrate, and, in principle, lowered the operating temperature of the hydrogen storage system. Although this did not result in the earlier requirements, it did show that adding catalysts could improve the thermodynamics and kinetics of the ab- and desorption. The research heuristic shifted from the exploration of alloys to the exploration of catalysts. Metal hydrides research in general increased as a result of this new hope of finding the right storage medium. Meanwhile, gaseous and liquid storage report the possibility of hydrogen pressure to 700 bar. At the start of the millennium research outcomes were published that suggested that certain carbon nanostructures could hold up to 60 wt% of hydrogen by means of adsorption. These findings led to a strong increase in research funding for these types of materials. Especially in 2002 and 2003 many articles in our dataset that deal with al types of nanostructures. Unfortunately, the results never matched the original findings and this disappointment led to a decrease in the amount of research performed in this subfield. From our network analysis we can however state that some research with nanostructures is still conducted in relation to hydrogen storage. Even though the hype has passed, some still hold their faith in the nanostructures (Sakintuna et al 2007). The warrants in the third period refer to the need for alternative energy sources and carriers. The argument is that hydrogen is the best alternative and that metal hydrides provide the best option for storage. While earlier specifications of conventional gasoline cars were taken as yardstick, now DOE research targets in the FreedomCAR project are used to support the claim that only metal hydrides have the potential to meet these targets.

Qualifiers, by definition, are statements that support the claim but do not directly refer to the data. We found that the competition between (future) technologies is especially visible in qualifiers. A typical qualifier is:

"This alloy is capable of storing enough hydrogen and a storage system like this would be much safer than pressurised hydrogen"

While the safety issue is not at the core of the reported research and not related to the data presented, it raises the relevance of the claim. Qualifiers like these are used during the whole period that we studied. Qualifiers may be used either in a positive framing, to support the superiority of the researcher's own solution, or in a negative framing in which other solutions are criticised. Positive and negative qualifiers appear in equal amounts in the articles we studied. The negative qualifiers relate to four issues that are used to criticise the other methods. First, the lack of *safety* of especially gaseous storage at high pressures. Second, the required *volume* by both liquid and gaseous storage, which is seen as being much higher. Third, the operating *temperature* of liquid hydrogen is seen as problematic and inefficient. Fourth, the low energy efficiency of both liquid and gaseous storage, because cooling and compression consumes a lot of energy. The volume argument is most used, as metal hydrides always do better in that respect, but is followed by other aspects as well. See the following example of the use of qualifiers:

The second possibility, compressed gas, is cheaper than liquid hydrogen but requires higher volumes and heavier containers to get a similar hydrogen density. In fact, it needs 4 or 5 times the volume of the present gasoline tank (i.e., about 250 L) and a safe and heavy container that can support 40 MPa of pressure. The large volume of the tank and the risks of the use of high pressures of hydrogen in conventional vehicles mean that compressed gas cannot be the definitive solution.(de la Casa-Lillo et al 2002)

Positive qualifiers also support the claim by relating to issues that do not directly follow from the data gathered in the research. We found four issues that support the future potential of metal hydrides. So, first, the safety argument of metal hydride storage is invoked. Second, the volume needed to store a given amount of hydrogen is allegedly less. Third, metal hydrides are said to bring along simplicity, as metal hydrides can operate at regular pressure and temperature ranges, which renders a storage system simple in design and use. Fourth, the costs of storage then are lower, because simplicity of the system results in low construction costs. One example of the use of positive qualifiers is:

"These systems have higher thermal conductivity and provide a simple design. Hence these systems make use of the hydrogen energy very promising for commercial applications, for example, one of great importance is automobile application."(Jain et al 1988)

The continued use of qualifiers marks the continuous competition between the different storage methods, and is especially visible in articles on metal hydride storage. Proponents of gaseous and liquid storage are less polemic, as their solutions are tried and tested in practice and rely less on arguments of future potential.

3.5 Conclusions

Competing technologies are well studied and well known phenomena, also in the domain of energy production and consumption. In this paper we investigated a less recognised phenomenon: the prolonged competition that takes place before there is any market activity. The generic promise of a hydrogen economy has been articulated into a prospective chain of hydrogen technologies, and more specifically, into a set of requirements for on-board storage. The competition between different hydrogen storage methods took place largely in terms of expectations of future performance, rather than current performance. Breakthroughs such as with the alanates in 1997, are especially significant in terms of fuelling new promises. Meeting the requirements is not a straightforward process and has taken several decades.

Our results suggest that it is possible and useful to add an extra, fourth, or rather 'zero' phase to Utterback's scheme of three phases in innovation processes: an 'expectation' phase that precedes the fluid phase. This is the phase in which both technology and markets are unarticulated: the competition occurs between projected performance in envisioned scenarios. We have drawn from the sociology of expectations and Toulmin's work on argumentation to trace the characteristics of the extra phase. The table we presented of Utterback's phases (Table 3.2) should thus be extended with an extra column of the expectation phase of development. We have tentatively filled this column with the results of our case study (Table 3.6). The important distinction between the competing technologies that we studied and those reported in the work of Utterback is the basis of competition. Competition takes place between imagined future solutions that result from R&D, political struggles, activism of NGO's and, occasionally, demonstration projects. What is at stake in the long run is a market share: in the short run it is a position in the relevant agendas of research institutes, laboratories of firms and government schemes, such as the DOE FreedomCar project. Expectations work is conducted by scientists and policy spokespersons to secure a position of their options in the relevant agendas. Three remarks on the 'expectation phase' should be made here. First, expectations, to be sure, will be important in the other phases as well, when products are available and firms compete for attention and market share. Second, the notion of 'phases' foremost stresses that competition will have different shapes in different settings, but does not necessarily suggest a smooth, stepwise or linear progress from one phase to the other. Yet, settings change and whether and how such changes of settings occur remains an empirical question. Third, the notion of 'phase' also suggest a short term phenomenon, while our case shows that such a period may take decades, hence stressing that the transformation of promise into requirement can be complicated and confusing.

Table 3.6: The expectation phase in an innovation process

	Expectation-phase
Product	Imagined future solutions
Process	R&D ranging from basic science to engineering
Organization	Dominated by knowledge producers and their policy supporters
Market	Research and policy agendas serve as selection environments
Competition	Techno-scientific communities and policy supporters
Basis of Competition	Expectations of future performance.

During several decades the development of hydrogen on-board storage solutions continued to be linked to the perspective of an endless potential of hydrogen as a sustainable energy carrier and the nearing end of the fossil fuel era. Over the years, different materials were studied, but progress has been limited in all three competing options. We observed that the technologies, in particular storage in metal hydrides, increasingly rely on the argument that their competitors cannot, fundamentally, make any progress at all. In other words, there is hope *because* there is disappointment. At the same time, the functional expectation of hydrogen storage as such should remain intact, otherwise the prospective chain of hydrogen will break down and required work on its components is in danger. In a situation of transforming complex technological systems, therefore, competing expectations introduce, sustain and use a delicate balance between hope and disappointment.

Acknowledgements

We thank Wouter Grooten and Maurice Oost for their contributions and both anonymous reviewers for their valuable suggestions.

4. Hydrogen prototype cars

4.1 Introduction[8]

This paper pursues the identification of dominance in prototype designs of hydrogen vehicles and more specifically of hydrogen passenger cars (HPCs). *Theoretically our analysis starts from dominant design theory.* Abernathy and Utterback (1978) originally defined *a dominant design as the most commonly used configuration for serving a purpose by using technology.* The concept has proved to be a fruitful source of innovation research and many scholars have used the dominant design concept (Anderson and Tushman 1990, Murmann and Frenken 2006, Henderson and Clark 1990, Suarez and Utterback 1995). The most salient aspect of the distinct definitions of dominant designs is that it has a market share larger than 50%.

Our paper pursues a further development of the implicit assumptions regarding the dominant design perspective. The general dominant design perspective assumes that selection between designs only happens after market introduction, and that performance improvement is an important criterion. Our main conjectures are: a) already in the pre-market introduction prototyping phase variation and selection processes take place, which do lead to a dominant prototype design; b) this dominance can only very partially be explained in terms of alignment with user preferences or updates of price and performance characteristics. Innovation trajectories have histories long before market introduction of assembled products and many designs are tried and tested in the form of prototypes. Arguably, selection also takes place in that phase, since not all prototyped designs make it to the market. An evolutionary development of designs can be expected as well as an evolution of the selection criteria that apply to the designs. So our general research question reads as follows: How do the dynamics of

8 This chapter is submitted for publication and was, in a slightly shorter version, presented at the 2010 DRUID conference as: Bakker, S., Van Lente, H. & Meeus, M. (2010) The Emergence of a Dominant Design in the Prototyping Phase – An Analysis of Hydrogen Car Prototypes, *Druid Summer Conference 2010*, London

selection and variation unfold in the prototyping phase, and how can we develop further dominant design thinking into the pre-market stage? More specifically we ask three questions: 1) to what extent do HPC prototype designs evolve into dominant prototype designs already during the pre-market phase?, 2) what kind of selection criteria and mechanisms apply in the absence of market forces that explain dominance of a HPC prototype, 3) how do strategic manoeuvres of HPC prototype producers impact the dominance process?

Our main theoretical claim is that the pre-selection of designs in the prototyping phase of the innovation process is based on the way in which sets of expectations about future performance of technological components and imitation behaviour of firms reinforce each other. The emphasis on expectations and imitation among car manufacturers is derived from some specific features of our case: prototypes of hydrogen passenger car (HPC).

We study the pre-market selection through a historical analysis of hydrogen vehicle prototyping in the automotive industry. The analysis contains both an overview of the designs used in the industry as a whole as well as an analysis of individual firms and their prototypes. This paper is structured as follows: first we will further discuss the assumptions and main focus of dominant design theory, as well as the selection mechanisms that are deemed relevant in explaining dominance. Next, we contrast that with our case of hydrogen car prototypes and develop an alternative framework for understanding the emergence of a dominant design in the prototyping phase. In the results sections we analyse forty years of hydrogen prototypes to derive the selection mechanisms that have taken place at the industry level as well as those that applied in the individual firm strategies.

4.2 Dominant Design theory

Dominant design literature has challenged and developed the variation assumptions of much innovation research by asking: why do designs become dominant? Table 4.1 provides an overview of selection criteria and mechanisms before and after market entry, which have been presented in the dominant design literature. For selection in the market, a distinction can be made between competition between successive dominant designs and the competition between multiple contenders in a new product class, for which no old design needs to be battled. For the pre-market phase, some selection mechanisms have been identified, but thorough insight is still lacking.

The most straightforward explanation of dominance of a design is that the best design outperforms any other design in terms of performance and price (Abernathy and Utterback 1978, Anderson and Tushman 1990, Christensen and Rosenbloom 1995). Anderson and Tushman (1990) have argued that the emergence of a new dominant design is preceded by a technological discontinuity that brings an order of magnitude improvement in price versus performance over the existing dominant design (Tushman and Anderson 1986). From the moment that the new design, or regime of designs, is introduced on the market, competition takes off between the old and the new regime, but also within the new regime. This so-called era of ferment results in the emergence of the new dominant design that will dominate until the next technological discontinuity (Suarez 2004).

Table 4.1: Selection of Dominant Designs in different phases

Phase	Successive dominant designs in the market	Dominant design in new product class in the market	Pre-market emergence of dominant design
Selection criteria and mechanisms	- superior **performance** and **price** (Abernathy and Utterback 1978, Anderson and Tushman 1990, Christensen and Rosenbloom 1995) - **compatibility** with existing DD (Hagedoorn et al 2001) - **regulation** (Islas 1999)	- superior **performance** (Frenken et al 1999, Rosenkopf and Nerkar 1999) - **first** to market or initial (niche) market leader (Hounshell 1985, Klepper 2002) - **network** externalities (Frenken et al 1999, Rosenkopf and Nerkar 1999) - **strategic** manoeuvring (Garud and Rappa 1994, Cusumano et al 1992, Liebowitz and Margolis 1995) - **standardization/regulation** (Hounshell 1985, Klepper 2002)	- promising **breakthroughs** in performance (Grindley 1995) - **regulation** (Islas 1999, Miller et al 1995) - **organizational** support (Wade 1995, Rosenkopf and Nerkar 1999). - **strategic manoeuvring** (Grindley 1995, Das and Van de Ven 2000, Garud et al 2002, Funk 2003) - **demonstration** of technical feasibility in a prototype (Suarez 2004)

The notion of technological discontinuities assumes on the one hand that performance can indeed be defined and measured for a given design and its competitors. On the other hand it assumes that performance measures are robust over time. For cases described in the dominant design literature, such as storage capacity for digital hard drives (Christensen et al 1998), this might be correct. However, in the case of many emerging technologies, performance on a single measure cannot be the explanation for the selections made and often some sort of negotiations take place to determine relevant criteria (Garud and Rappa 1994, Das and Van de Ven 2000).

Besides performance, other selection criteria have been proposed in the dominant design literature. These include economies of scale in niche markets in the early stages of diffusion (Frenken et al 1999): the advantage of a design gained through network externalities in its early stage of market adoption (Hagedoorn et al 2001, Rosenkopf and Nerkar 1999, Hounshell 1985, Klepper 2002). These mechanisms can only take effect once a (niche) market has been established and occupied. The same holds in that respect for licensing of standards and strategic manoeuvring as in the case of VHS video recorders (Cusumano et al 1992). Also, regulatory changes can create relative advantages for a specific design over others, and foster the emergence of a new dominant design (Islas 1999, Miller et al 1995). Islas, for instance, concludes from a case on gas turbine development that newly imposed regulation hampered the existing designs and favoured the new technology.

The aforementioned studies deal mainly with designs that are lined-up for market entry and focus more on conditions for successful entry (such as standardization efforts and other forms of cooperation between firms) than on the battle for optimal designs as such (Wade 1995, Grindley 1995). These studies deal with the period right before and after market introduction. This is the phase that Islas[9], citing Willinger and Zuscovitch (1993) and inspired by Kuhn (1992), describes as the pre-paradigmatic phase: the one that precedes the establishment of a new paradigm in a certain market. During this phase, firms seek support for their design and seek alliances with other firms to make sure that their common design makes a strong competitor.

There is only one paper, by Suarez (2004) on competition between multiple designs in the pre-market introduction phase in which the role of prototypes is taken into account. Suarez (2004 p.279-283) describes a five stage process of becoming dominant. In the first phase pioneering firms or research groups start doing applied R&D pursuing the production of new commercial products. The second phase is marked by the appearance of a first working prototype of the new product. The third phase in the dominance process is the launching of the first commercial product, and finally there are phases four and five in which a clear early frontrunner appears, and one of the alternative designs becomes dominant. In phase II, technological feasibility sets the stage for competing actors to show their technological superiority and introduce the best performing prototype design. As in most of the dominant design literature, he explicitly claims that it is technical superior performance that is decisive for a design to become dominant (Suarez 2004 p.282).

However, in the following section we discuss why superior performance can not be the only criterion for selection in the case of hydrogen prototype cars and why other criteria should be added to explain the emergence of a dominant design in the prototyping phase.

4.3 Our case: prototypes of hydrogen passenger cars

Our focus on selection in the pre-market stage derives from the specific nature of our case: prototypes of hydrogen passenger cars (HPCs). The emergence of hydrogen technologies in the car industry reveals two issues that so far have not been addressed by explanations on the emergence of dominant designs. First, hydrogen has emerged as a potential technological discontinuity that might challenge the old dominant design in the future, but it is at least an order of magnitude underperforming the current design in terms of price versus performance (Romm 2004). This potential discontinuity is thus developed on the basis of either high expectations of technological progress or expected changes in market selection criteria that would benefit this option to a great extent. Second, there is no market for hydrogen vehicles but nonetheless the different designs are in competition amongst each other.

Although hydrogen as energy carrier is not a technological discontinuity at present, it could very well become one. The technology itself may improve to a great extent, both in terms of performance

9 In the case of gas turbines, market entry is not a sharply defined moment in time, the diffusion process is slow and development and adjustment of designs continues. In such a case pre-market selection of viable designs coincides with market selection and the selection of dominant designs is difficult to ascribe to either a pre-market or a market phase.

and production costs. And with increasing pressure on the car industry to develop more sustainable cars, the hydrogen option might be a necessity in the future. Being a radical move away from the gasoline powered internal combustion engine paradigm, the hydrogen prototypes demonstrate a set of new opportunities and heuristics that gain momentum. In this sense prototypes are technological platforms that define technological opportunities and barriers for further technological and market trials (Dosi 1988). Car manufacturers have experimented with the technology and have shown their results to the wider public during the big motor shows and through press releases. Even though no commercial hydrogen passenger cars are available today and no one can tell for sure whether there will ever be one, car manufacturers do claim that they are serious about HPCs and that they consider hydrogen to be a very serious contender in the race for the fuel of the future (van den Hoed 2005). This is exemplified by the fact that in September 2009, Daimler, Ford, GM, Honda, Hyundai, Renault/ Nissan and Toyota released a Letter of Understanding on the development and market introduction of fuel cell vehicles in 2015.

Given this early stage of HPC development, hydrogen is a *prospective* rather than an actual technological option and includes many different configurations of the production of hydrogen (natural gas, coal, electrolysis, etc) and use of hydrogen in cars. There are various combinations of storage methods and conversion technologies, and envisioned hydrogen energy systems differ greatly (McDowall and Eames 2006). So, while hydrogen is promoted as the fuel of the future, a competition exists between the different technological options that can constitute the hydrogen car of the future.
According to Suarez' phase II of the dominance process, prototypes serve as a test bed and demonstrator of technological progress. This phase sets the stage for competing actors to show their technological superiority, and to select and introduce the best performing prototype design (Suarez 2004 p. 282). R&D management literature is slightly more realistic about the 'superiority' claims of prototypes that are so prominent in the dominant design literature. In the R&D management literature prototypes are viewed upon as steps in problem solving cycles in the research and development activities of firms (Clark et al 1987, Thomke et al 1998, Thomke 1998). Prototypes are part of an iterative learning process, with trial and error. Outcomes of research or engineering activities are applied in a prototype and used to test or prove a scientific or engineering concept: does it work? Or, when a number of technological novelties are fitted together in a prototype to test or prove their compatibility: does this configuration work?
Both the R&D literature and the dominant design literature concentrate on the *in-firm use* of the prototype. Many prototypes, however, leave the laboratory and industry gates and serve a purpose beyond the firm or research department (Rip and Schot 2002). Intended or not, they give a high cost signal about the promising technologies that a firm considers valuable for its strategy and this holds especially for the hydrogen prototypes. Even when a prototype does not show superior performance with respect to the existing dominant design, it can still demonstrate the high potential of the technology, since promising technologies are not necessarily superior performing technologies. A prototype can display a proof of principle of a promising technology and serve as a platform for

wider expectations of the technologies that are applied: each prototype, we argue, embodies a set of technological and functional expectations. Prototypes, thus, convey messages to a large external audience about the useful properties of an innovative technology or about the contours of a future market, and can be used to convince other actors within or outside the firm[10]. This typically applies in the case of hydrogen passenger cars, which are taken to large fairs and exhibited as a serious bid in the hydrogen future race.

The science and technology studies (STS) literature emphasizes that prototypes configure future alignments between the materiality of the technology and the beliefs and behaviour of its users, the non-material. They are, in other words, considered to be *working artefacts* that help to shape future worlds (Suchman et al 2002, Danholt 2005, Wilkie 2008) by engaging new technologies with its future context of use. Prototypes can even be used to influence policy making by, for instance, convincing regulating bodies that firms already work on zero-emission vehicles (ZEV's) and that stringent market policies, such as the well known Californian ZEV regulation (CARB 2008, Collantes and Sperling 2008), are not necessary. Therefore we have to ask the question what drives selection in this phase, given that there is more speculation than certainty on technological opportunities, despite technological progress.

To sum up, there is no such thing as a fully naïve, non-strategic prototype that only serves the company's internal research trajectory. Also there will be no solely strategic prototype that has no relation with the actual research trajectories of the company. Prototypes are too expensive to function only as a marketing tool and presented with too much enthusiasm to be mere R&D tools. According to a leading researcher in the industry a prototype is, in the first place, a tool to test the components, integrated and in real use. Second it is a means to communicate to the firm's management what the research department has achieved. And, third it is a means for the firm to demonstrate its activities and achievements towards the outside world and to sponsors of the research project.

Toward an alternative framework: technological expectations and strategic manoeuvring

Given the multiple roles of prototypes in the innovation process, how does dominant design theory integrate prototyping in its framework, and to what extent does this fit the case of HPC prototypes?

As said, the HPC prototype case can not easily be fitted with Suarez' dominance process. *First*, at present there is not a single measure that uniquely describes the technological performance of a hydrogen car. HPC prototype cars must meet several types of performance requirements such as: speed, range, various emission levels, high(-er) energy efficiency, and safety. These design requirements constrain each other until today. And *second*, the measures that are available may change due to changes in consumer preferences and governmental regulations. Hence benchmarking the design options on current performance and future targets remains rather complicated. Instead, one can expect a co-evolution of the design in the making and the targets that design should be able to meet.

10

One element of dominant design theory that will hold in the case of hydrogen passenger cars is the notion that ultimately only one design can be dominant when the market is entered. Network externalities will provide the dominant design with significant benefits and firms will therefore not choose a design that diverges too much from the dominant one.. For instance, the refuelling infrastructure will be geared towards the dominant storage option and other options would then require a separate infrastructure. Therefore, firms must keep an eye on each other's activities and design choices and will most probably follow the leading firms with the most promising designs. For us the question is thus whether such a convergence in hydrogen car designs has occurred and, if so, how the prototyping strategies of individual car manufacturers have evolved to let one prototype design become dominant.

In our framework we focus on two factors: first, the role of technological expectations, and second how these expectation are moulded, and transformed in the strategic manoeuvring of the firms. Both are very much interrelated. Technological expectations, dealing with expected future levels of performance of different design options and components, may guide firms in their selection of technologies to develop and incorporate in prototype cars. Strategic manoeuvring deals mostly with the amount of variations, or technological paths, that any firm may choose to pursue and the extent to which they either lead or follow the developments in the industry. These factors are interrelated because technological expectations gain traction and appeal when they are shared by a majority of significant actors (Borup et al 2006, Konrad 2006). Thus, if a group of firms chooses to develop a specific design, others might derive high expectations of that design and no design would ever survive eventual market introduction if only one firm were to endorse it.

Two basic components in any hydrogen car define the design space for HPC prototypes: the conversion of hydrogen to power and the storage of hydrogen on-board the vehicle. Within the design space, eight different configurations or technological paths are possible as there are two conversion options and four storage options or each. Car manufacturers do have distinct choices in moving through the design space, and can combine distinct paths in distinct ways. We discern the main dimensions in the strategies of prototype manufacturers:

1. The number of prototype models produced: higher numbers represent a sincere investment in the HPC trajectory and are indicative of stronger expectations as to the HPC trajectory.
2. The technological paths represented by prototypes: where do car manufacturers place their bets, in which technologies do they firmly believe?
   - The sequence in which car manufacturers enter or exit these paths, reveal the stability of their beliefs and expectations towards a certain existing or 'new' pathway.
   - Whether they engage in multiple paths in parallel or sequentially: car manufacturers can stick to one or move over different paths and this is another dimension of the stability of technological expectations. Being in more paths simultaneously implies that technological expectations are still fermenting

- The timing of these choices in terms of being first movers, early movers or late followers. Being a first mover implies that a company has identified a meaningful new technological opportunity, which extends the set of technological expectations. Late followers are merely imitators that confirm the feasibility of a path. A large number of imitators is indicative of the transformation of a technological expectation into a confirmed feasible option.

These dimensions enable us to distinguish between distinct types of strategic manoeuvring in the HPC prototype design space. We discern two main strategies that can be refined on several dimensions. A *deep, and specialized strategy* means that companies release prototypes that focus on one path only and that there is a large number of prototypes produced, which also means that prototypes are updated at a relative high frequency. A *broad and diversified strategy* means that a company has prototypes in distinct paths, and regularly updates its prototype portfolio. A broad and diversified strategy implies that car companies exhibit and release two or more prototypes in parallel. Car manufacturers will keep on doing so as long as their engineers hold positive expectations of either the storage methods, or the conversion technology for a specific prototype.

Because not all firms will develop the same designs and underlying technologies from the start, it is likely that the early years of prototyping activities show high variation. A number of first movers will open a certain technological path with their vehicles and other firms may choose to enter that path later on or open up another path altogether. If a dominant design is to arise, the majority of car manufacturers need to positively select a single path. As a consequence, there will be a shakeout of the other designs that are deemed unviable for further development.

4.4 Methodology

To establish our unit of analysis, we follow Murmann and Frenken (2006) and distinguish between two levels at which the competition can take place. At the system level, hydrogen challenges the gasoline powered car and all its surrounding elements such as fuel infrastructures, maintenance stations, etcetera. However, until now there is no full or limited competition for dominance, as defined by Anderson and Tushman (1990), at the system level. At the subsystem level, shaped by the components that make up the hydrogen car, we do see competition even while there is no product on the market. Our study focuses on this level of aggregation, the core components of the challenging technological system.

First, we try to show to what extent the whole population of manufacturers converge or diverge on the technologies and configurations they explore and whether or not a dominant design arises. And second, we study the selection criteria that apply by tracing technological performance, strategic manoeuvring and governmental regulations that apply, or were expected to apply, to the to the car industry.

The diversity in proposed hydrogen technologies is reflected by the range of hydrogen prototypes that have appeared over the last forty years. In the prototypes, different technologies have been used in different configurations and designs. We compiled a database of 224 prototypes of hydrogen cars. This data was gathered through an online search, using mainly websites dedicated to hydrogen vehicles[11], car manufacturers' websites and general car news sites. Additionally, this search was supported by already existing overviews[12] of hydrogen models, by visits to several car shows (Amsterdam, Geneva) and validated by industry researchers. Buses, trucks, and utility vehicles were excluded from the database. Several technological specifications were included in the database: brand, year, storage method, amount of hydrogen stored, conversion technology used, manufacturer of the fuel cell or engine, range, and maximum speed.

In this paper we consider the hydrogen storage method and the energy conversion technology as variables (see Table 4.2). The specifications of the prototypes were then plotted on a time line, showing either convergence (towards a majority of car manufacturers enter into a design path) or divergence over time (many different designs, all with few adherents).

Table 4.2: Storage and energy conversion technologies

Storage method			
Gaseous Hydrogen (GH)	Liquid Hydrogen (LH)	Metal Hydrides (MH)	Methanol (Meth)
Energy conversion technology			
Fuel Cell (fuel cell)	Internal Combustion Engine (ICE)	Bivalent ICE (Biv ICE)	

The limitations of our data are the following. Our search method does not necessarily generate all prototypes ever built, and for some prototypes not all specifications are available. This could be the result of secretiveness on the side of manufacturers, although manufacturers seem to use their prototypes as communication tools as well, and share most of the information. Certainly for the more recent models this data is freely available. For the older prototypes some data is probably missing. Still, we hold that the database is adequate for our purposes and is certainly accurate for the last ten years, when the majority of models were produced. In the analysis of the selection of individual technological options, we used all prototypes in the database. For the analysis of configurations we used only those prototypes of which both the storage and conversion technology are known and we took only the prototypes from incumbent car manufacturers. The prototypes from mother firms are taken together under the header of the mother firm instead of the separate brands (e.g. BMW/ Mini, GM/Chevrolet). Some of the prototypes were produced in small series, most were produced

11 www.netinform.net/h2/, www.hydrogencarsnow.com, consulted from May 2008-March 2009

12 Walter, Thomas (2007). Database: 04-20-2007, pp. 1 – 37

individually. In our analysis we do not take this into account, each prototype model counts as one data point.

4.5 Results: components and configurations

While the first hydrogen car, consisting of a single piston combustion engine, was developed already in 1807, serious development of hydrogen vehicles started only in the mid 1970s. In those days most hydrogen vehicles were existing models, adapted or retrofitted to run on hydrogen. Only since the 1990s have manufacturers begun to develop dedicated hydrogen vehicles of which the whole design is based on its hydrogen drivetrain. The number of prototypes developed shows a steady growth up to the mid 1990s and since the end of the 1990s the number of prototypes developed each years increases sharply. All major car companies are involved from there onwards. The cumulative prototype production increases from 32 in 1997 up to 224 in 2008 (Figure 4.1).

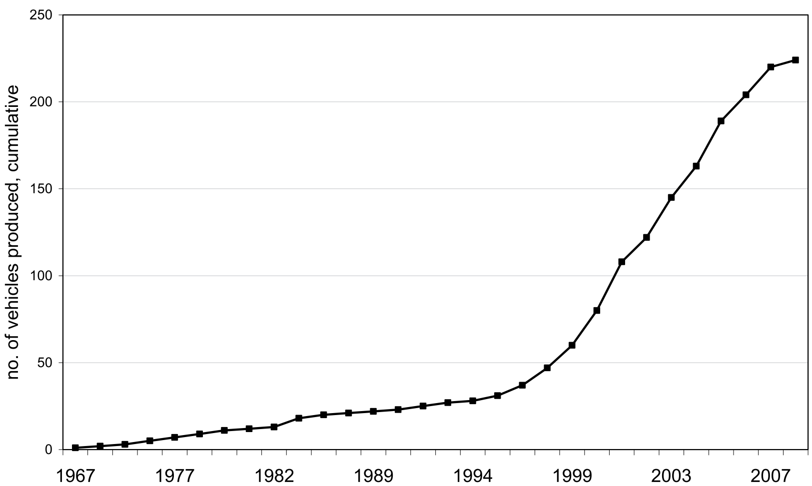

Figure 4.1: Cumulative number of hydrogen prototypes

The fast majority of the prototypes are developed by the incumbent firms in the automotive industry whereas only 18% of the prototypes is built by universities or as part of research networks. This suggests that the automotive industry responds to perceived needs for a greening of the industry. Apparently, car manufacturers share a sense of urgency to develop alternatives for personal mobility and hydrogen is one of their options.

The largest share of prototypes has been developed after 1999. As from 1967 until 1999 48 prototypes were build, which means that there is an average production of 1.5 prototypes per annum. Between 1999 and 2008 the bulk of the prototypes has been developed: 192 out of 224. In a relatively short period of time the growth of the number of prototypes has exploded, and went from 1.5 per annum to 20.2 prototypes on average per year.

The sudden surge of hydrogen prototypes is most probably caused by announced or expected governmental regulations, of which the Californian emissions directive in the 1990s[13] was the most prominent. Hydrogen was seen as the most promising answer to these requirements because of its versatility in terms of both production and use. Furthermore, the development of fuel cells raised technological expectations as to their efficiency and the possibility of lowering the cost of production.

Energy conversion technology

From our database we conclude that there are two main options for the conversion of hydrogen into power. These are: 1) the hydrogen fuel cell (fuel cell) as main energy convertor and 2) the internal combustion engine (ICE). While the fuel cell is often seen as one of the main drivers for hydrogen as fuel of the future (because of its high efficiency), the combustion engine is also considered by a number of firms. In the second half of the 1990s a sharp increase in the number of fuel cell prototypes sets in, and in 1998 the cumulative number of fuel cell designs overtakes the combustion engines.

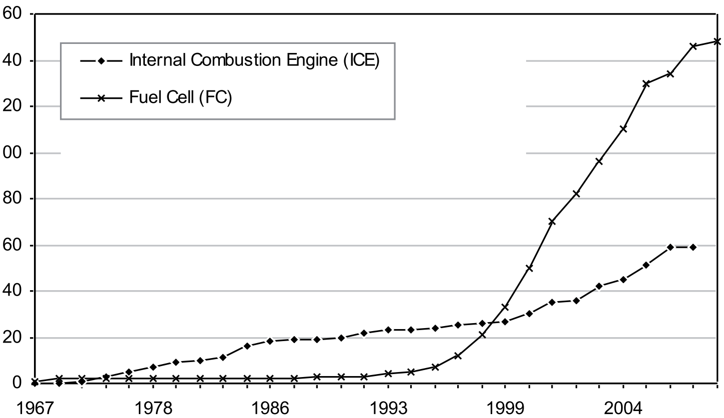

Figure 4.2: Cumulative numbers of different types of conversion technology used

From then on, the fuel cell is dominant in the prototypes (Figure 4.2), which are either vehicles that run primarily on their fuel cell or vehicles that run primarily on a plug-in battery which is supported by a (smaller) hydrogen fuel cell system. A prototype that primarily runs on its fuel cell will always be equipped with a battery or capacitor as buffer for the electricity generated by the fuel cell. The battery is then used during acceleration for instance. Also, it can be used as a storage medium for energy restored by a regenerative braking system.

Fuel Cells

While a number of fuel cell types are available, the favourite choice in the automotive industry is the proton exchange membrane (PEM) fuel cell. The reason is its high efficiency at low temperatures of

13 Personal communication with former Daimler fuel cell engineer

operation (<100°C), whereas other types operate only at temperatures of 400 degrees and higher. It clearly is the dominant choice and it could be interpreted as an example of a dominant design in the pre-market phase. Dedicated fuel cell producers like Ballard and UTC Power together provide 38% of the fuel cells in our database's prototypes. Car manufacturers themselves have also developed and produced fuel cells, to be used in their own prototypes or in those of others. Most notable here is GM: 12% of all prototypes use a GM fuel cell. Also Honda and Toyota develop fuel cells themselves that are used in various other car brands' prototypes.

On-board storage

While the fuel cell is often seen as a true technological enabler (creating an opportunity) of the hydrogen vision, on-board hydrogen storage is seen as a constraint. Because of the low energy density (per volume) of hydrogen as a gas under ambient conditions, it is a challenge to take enough hydrogen on board to allow for an acceptable range without refuelling. The two obvious ways of doing so are pressurising or liquefying the gas. Both require huge amounts of energy, giving energy losses up to 20% for compression and about 30% for liquefying (Department of Energy 2002). On top of that, gaseous hydrogen under high pressure is considered as a safety hazard. Liquefied hydrogen suffers losses due to so-called boil-off: it is impossible to prevent any hydrogen to evaporate and the resulting gas has to be released. As alternatives to these relatively simple solutions, a number of more innovative and complex solutions have been proposed. Most attention is given to storage in metal hydrides. Here, hydrogen gas is fed to a tank containing a metal powder and is absorbed as hydrogen atoms in the metal's atomic lattice to form a metal hydride. Using metal hydrides, the hydrogen can be stored with a higher volumetric density than that of liquid hydrogen. The main backdrop, however, is the weight of the total storage system, due to the weight of the metal used. Also the rate of the ab- and desorption (increasing refuelling time), and operating temperatures are still problematic. To circumvent the storage issue, the firms have also experimented with reformers that produce hydrogen from methanol (Meth) on-board the vehicles. This method allows the vehicles to be fuelled with a liquid hydrocarbon and takes away the need for a dedicated hydrogen infrastructure. Even though long ranges could be achieved with the reforming options, all firms have dropped this option from their portfolios. Other competition for gaseous and liquid storage comes from storage in chemical hydrides (bonding the hydrogen to a liquid chemical substance such as ammonia or hydrazine), solid storage in nanomaterials or rather exotic methods such as clathrates (ice-like structures capturing the hydrogen). These solutions however are far from practically usable and seldomly used in prototypes.

In the meantime, while research is conducted on the alternatives, the automotive industry uses liquid and gaseous storage systems in their prototypes. Metal hydrides (MH) have been used, but it seems that the industry has abandoned them. Nonetheless, as can be seen from the research activities in the US and the EU, expectations of metal hydrides are still very much alive (van Lente and Bakker 2010). A closer look at the storage methods, as displayed in Figure 4.3, reveals an initial dominance of liquid hydrogen storage (LH). Since the late 1990s this dominance was taken over by compressed gas.

Between 1999 and 2008, 69% of all prototypes hold a high-pressure tank. This coincides with the increase of the use of fuel cells, both in pure fuel cells and the battery/fuel cell hybrids, in that period.

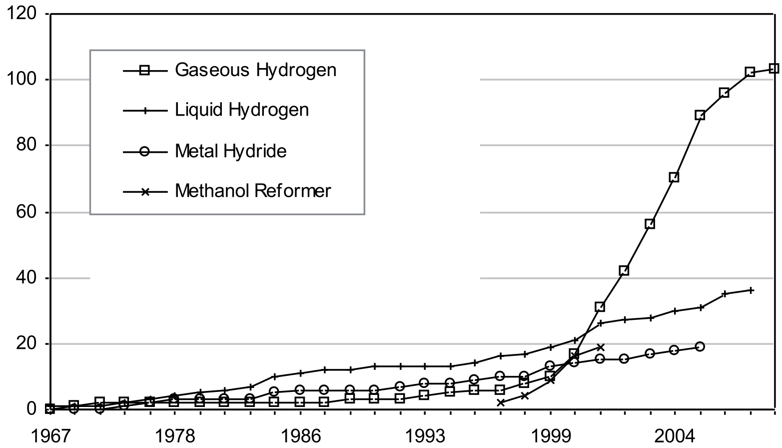

Figure 4.3: Cumulative numbers of storage methods used

The dominance of gaseous storage (CGH) in prototypes does not necessarily imply a definitive choice for that technology. On the one hand, some companies, again most notably BMW, hold on to liquid storage because it enables them to store more hydrogen.

Configurations

The conversion and hydrogen storage configurations that are used in the prototypes vary over time. From the multitude of designs, with a peak in the late 1990s, one designs stands out as the dominant design for the hydrogen car, see Figure 4.4. This is the fuel cell vehicle with gaseous hydrogen storage. This configuration makes use of the PEM fuel cell in combination with gaseous storage at either 350 or 700 bar. In the following section we will clarify the selection criteria that were applied to hydrogen prototypes.

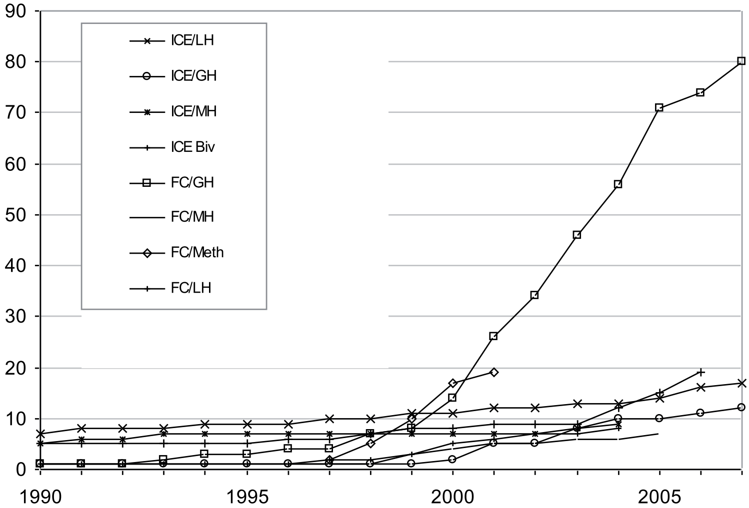

Figure 4.4: configurations used in hydrogen prototypes

4.6 Selection criteria and mechanisms

In this section we analyze the criteria and mechanisms of the selection of designs that have led to the pre-market emergence of a dominant design of the hydrogen passenger car. The prototypes of the 14 most active firms are taken into account in this analysis. The first mechanism that we investigate is the firms' strategies of moving between the different design paths. Second, we investigate the role of technological performance and expectations of further progress.

Technological performance as selection criterion

In the case of hydrogen vehicles one performance measure stands out as the most discussed and, next to production costs, most challenging barrier to commercialization: the maximum range of the vehicle. Automakers shared the notion in the 1990s that a car should be able to go at least 480 kilometres without refuelling (Eisler 2009). Success on this measure may not be critical for all purposes of the prototype (a test of the prototype as 'configuration that works' does not necessarily rely on the range), but it is a success in terms of engineering and it is used to communicate the firms' achievements to a wider audience. The challenge to increase the range of the vehicle is twofold. First, the car manufacturers have tried to improve the overall efficiency of the vehicles. And second, the manufacturers have explored a multitude of storage options in order to store enough hydrogen on-board the vehicle to give it as much range as possible.

Another important performance criterion is set by governmental regulations. It was the Californian Air Resources Board (CARB) that initially set the stage for the car industry's attempts to develop zero-emission vehicles. Battery-electric and hydrogen vehicles were developed in response to this regulation. As the CARB called for zero-emission vehicles, not all hydrogen vehicles were able to pass the requirements. For instance, the methanol reformer option was ruled out and also the ICE vehicles were not seen as true zero-emission as they still emit NOx. More recent are Japanese and EU regulations, and also in some states in the US that favour low-emission vehicles, which in theory widens the scope for hydrogen vehicles. Nonetheless, car firms have opted for the zero-emission (on a CO2 basis at least) in the last years. They have done so to increase the impact of hydrogen vehicles on the average emission levels of their full fleets of cars they sell.

Table 4.3: Summary of hydrogen development and progress in 14 firms, the number of models and the progress figures refer to the preferred design of the manufacturers as listed the table. *Both Ford and Fiat have no clear preferred design, but FC/GH is prominent in their portfolios.

	Preferred design	No of models	Progress on range*	Progress on speed*	Platform	Fleet	Use
Daimler	FC/GH	8	150 → 400	120 → 170	Midsize	300	Lease
Toyota	FC/GH	5	175 → 500	100 → 150	Midsize	60	Lease
Honda	FC/GH	7	180 → 430	140 → 160	Midsize, dedicated	200	Lease
Ford	FC/GH*	5	160 → 560	128 → 140	SUV	30	Demo
GM/Opel	FC/GH	6	130 → 480	128 → 160	SUV/midsize	110	Demo
Mazda	Biv ICE/GH	2	200	60 → n/a	Midsize	n/a	Lease
BMW	Biv ICE/LH	13	300	215 → 230	Top class sedans	100	Loan
VW	FC/GH	3	150→ 140	115→ 150	SUV	no	test
Audi	FC/GH	2	220→ 250	175→ 160	Midsize SUV	no	test
Daihatsu	FC/GH	3	120→ 153	105-n/a	MPV	no	test
Fiat	FC/GH*	2	140→ 220	100→130	Small (Panda)	no	test
Hyundai	FC/GH	4	160→ 576	124→160	SUV	no	test
Peugeot	FC/GH	2	250→ 350	95→ 130	Midsize	no	test
Suzuki	FC/GH	2	130→ 200	110	Midsize	no	test

Table 4.3 summarizes the development that has taken place at the fourteen leading manufacturers. It is clear that those firms that have entered the dominant FC/GH trajectory have made most progress in terms of range and speed. This was done through increased hydrogen pressures, but also through increased efficiencies of the entire drivetrain. Even though top speeds are still lacking (compared to current cars and BMW's ICE models) these firms have made progress in that respect as well. The very fact that they have invested in fuel cells development signals the positive expectations these firms have held of this initially and to some extent still underperforming option. The (potential) high-efficiency of fuel cells has kept them on that trajectory, knowing that future regulation and fuel price developments would shape different selection environments than is the case for current cars.

Also, the firms that have embraced the FC/GH design seem most determined to stay on their trajectory. This is signalled through public statements, manufacturer's coalitions such as the Californian Fuel Cell Partnership, but also materialized in the form of small series of vehicles, lease-programs and most notably perhaps by Honda's dedicated hydrogen platform. Progress in range and top speeds could have been achieved through liquid storage and on-board reforming, but these were dropped by most firms due to poor efficiency and emission standards. Apart from the prototyping leaders, the rest of the industry has merely followed as and these firms have also not produced fleets of hydrogen vehicles or developed dedicated hydrogen platforms.
Even though the range of fuel cell vehicles has increased, a number of barriers to commercialization remain. First and foremost is the cost of the fuel cell and storage systems. Current prototypes cost about a million US dollars to produce[14]. Lower costs can be achieved through higher production volumes and much is done to decrease the amount of platinum catalyst in the fuel cells. Other issues remain as well: these include the lifetime of fuel cells (as measured in operating hours), size and weight of the cells and their cold start capability.

Strategic behaviour of firms

Different firms have taken different routes and applied different strategies. Some have been leaders, others have merely followed. In the following we combine both a historical analysis of the firms' search routes and a qualitative analysis of their statements, to reconstruct what strategies they have applied to their development trajectories and to what extent technological performance played a role in these. The fact that a dominant prototype design has emerged cannot be explained as a consequence of the adoption of similar strategies by all firms. The 14 car manufacturers have all chosen their own unique strategies and have unique patterns of followed paths.

Figure 4.5 displays the different configurations that car manufacturers applied in their HPC prototypes over a period of thirty years 1967-2007. The co-evolution of different paths of HPC trajectories can be divided in three phases. Phase I covers the period from 1967 up to and including 1993. The first phase is marked by the initiation of three paths: FC/LH, ICE/MH, and ICE/Biv. These are paths are started by Daimler, GM, and BMW. In phase II, from 1994 to 2000, there is a sharp increase in the number of paths that were explored. The *broadening* of the number of paths is considerable and grows from three in phase I to six in phase II. Daimler exits the ICE/MH path, and acts as a first mover in three different paths: ICE/GH, FC/GH, and FC/Meth. Between 1994 and 2001, 22 prototype HPCs were developed in total. This relatively higher number in a shorter time period is indicative of quite some new entrants such as Toyota, Honda, Mitsubishi, Hyundai, VW, and Ford. These firms all enter with prototypes in the fuel cell paths.

14 Toyota Targets $50,000 Price for First Hydrogen Car (Update2) Businessweek, May 06, 2010

Phase III, 2001-2007, is characterized by a remarkable *deepening* of paths in general and the addition of the ICE/LH by BMW. All in all 65 new prototypes were developed and a large majority (41) of these is found in the dominant FC/GH path. Only sixteen are powered by combustion engines.

Figure 4.5: Technological trajectories of individual firms

Table 4.4: Summary of the strategies applied by the 14 firms

	No. of models	No. of paths	First Mover	Early follower	Late follower	Strategy
BMW	13	2	+2			Deep
Daimler	20	5	+4	+1		Broad, Deep
Toyota	10	3	+1	+1	+1	Deep
Honda	9	3	+1	+2		Deep
Ford	11	4	+2		+2	Broad
GM/Opel	12	5	+1	+3	+1	Broad
Mazda	7	4		+1	+3	Broad
VW	5	4		+1	+3	Broad
Audi	2	2			+2	Deep
Daihatsu	4	2		+2		Deep
Fiat	3	2		+1	+1	Broad, Deep
Hyundai	5	2	+1		+1	Deep
Peugeot	2	1		+1		Deep
Suzuki	2	1			+1	Deep

The shear existence of a dominant prototype design of HPCs is a little miracle looking at the enormous diversity of release strategies of HPC prototypes over time. The most prominent car manufacturers in terms of the first mover frequency and the number of HPC prototypes are BMW and Daimler. These two companies have the most distinct strategies and, remarkably, BMW has *never presented* prototypes in the paths entered by Daimler. If strategies of all passenger car manufacturers would have evolved in this way, a dominant prototype design would not have emerged. In the following we elaborate on the manoeuvring of BMW and Daimler first and, second, we describe the manoeuvring of the other firms to explain why and how the dominant design did emerge as a result of their strategies, technological progress and expectations of further progress. A summary of the strategies is provided in Table 4.4.

BMW

From the start BMW has opted for the use of combustion engines and it has stuck to the ICE paths. It opened the ICE/Biv path and as of phase III BMW differentiated with the ICE/LH path. BMW really behaves conform a path-dependency model, and sticks to a specific passenger car template that fulfils standards range and speed requirements of the customers. BMW's strategy is partially parallel, but within ICE paths only. BMW kept on updating HPC prototypes in the ICE/Biv path at a high rate: 10 prototypes in 28 years, and in the ICE/LH path it presented 3 prototypes in three years. BMW's update frequency seems to be affected little by rivalry. It had only 5 competing prototypes with the

ICE/Biv design, from Ford, Mazda and Fiat. In the ICE/LH path, there were no early or late followers at all. Compared to the paths that were opened up by Daimler as a first mover the numbers of early and late followers of BMW HPC prototypes did not come close to those generated by the prototype designs of Daimler.

To provide an explanation of BMW's focus on the ICE paths, its tagline for hydrogen related matters is a good starting point: *"We stop emissions. Not emotions[15]"*. All of BMW's hydrogen vehicles were based on their high-end luxury vehicles and were powered by an ICE because of its power output and because of the relative low cost of these engines. The power provided by the engine is reflected in their relatively high top speeds (200-230 km/h) as compared to fuel cell vehicles and this is the emotional aspect of cars that BMW has tried to preserve. In doing so, it avoids the sobering, or more generally reshaping of customer preferences. The downside of ICE's is their low energy efficiency, which is reflected in the short ranges of the BMW models. To overcome this barrier, the company has developed a number of bivalent vehicles, which are able to run on both hydrogen as well as gasoline. With these fuels combined, top ranges of 500 km were achieved and drivers are able to refuel in the absence of hydrogen filling stations, making them an interesting option for a transition phase in which filling stations are low in numbers. In contrast, BMW's pure (liquid) hydrogen cars have not been able to go further than 300 km without refuelling. The inefficiency of ICE's and the remaining NOx emissions have pushed BMW to the point that the firm is reluctant to stay on this path[16] and it might switch to fuel cells like the rest of the industry.

Daimler

Among the big HPC prototype producers Daimler turns out to have been first mover in four of the eight paths[17]. The spreading of bets starts in 1994 when Daimler produces its first fuel cell prototype and eventually differentiates into three distinct paths: FC/GH, FC/Meth, and FC/LH. During phase II Daimler explored four paths simultaneously. As per 2002, in phase III, Daimler significantly narrows down its prototype production to two main paths and produced updates of FC/GH prototypes on an annual basis. In parallel, Daimler moves back to its initial ICE path but it does so in vans rather than compact cars. Compared to BMW's imitators, Daimler first moves generated much more followers that indeed also updated their prototypes at high frequencies. To illustrate, the FC/GH path accounts for 48 out of the 105 HPC prototypes.

There is a notable difference between the follower dynamics in the paths that Daimler first moved into. The most successful path, FC/GH, takes off relatively slow with only 7 prototypes in phase II (1994-2000). There were only three companies that followed suit: Ford (with its first HPC prototype ever in 1999), Honda and Hyundai. The FC/Meth path develops much faster in terms of the number of

15 www.bmw.com

16 Hesitation towards the ICE desigs speaks from a BMW press statement that was released through the Clean Energy Partnership on 10-12-2009: "BWM setzt weiter auf Wasserstoff"

17 We have included here the Chrysler prototypes that were developed under the heading of DaimlerChrysler between 1998 and 2007.

releases of prototypes, which amounted to 11 between 1996 and 2000. Yet, the last prototypes in this path were released in 2001. Another fuel cell path, FC/MH that was opened up by Toyota, produced 6 prototypes between 1996 and 2000, which is a rate comparable to the FC/GH path. Yet, the higher initial production rates in both the FC/MH and FC/Meth did not continue after the swift take-off. This is quite a contrast compared to the FC/GH path. In fact, the large majority of car manufacturers that had been active in FC/MH, FC/Meth, and FC/LH moved over to the FC/GH path from 2001 onwards, with only one exception and that was Mazda.

Being the main pioneers of hydrogen technology, Daimler already presented a prototype model in 1975: a small van equipped with an internal combustion engine and metal hydride hydrogen storage system. Daimler continued experimenting with vans, as they provide a spacious platform for hydrogen storage systems. But in 1984 and 1986 it also used two luxury cars as platform. The range of these vehicles was rather limited, 70 km with the 1986 model whereas and 150 km with the 1984 model. Clearly, performance was not the major issue here and these vehicles served as experimentation platforms for the use of hydrogen and the hydride storage systems. Daimler's last experiment with hydrides was presented in 1991 in a futuristic experimental model of which no performance numbers were released. Afterwards, hydrogen combustion engines were only used in the Sprinter type van, all equipped with high pressure storage. From 1994 Daimler began to use fuel cells as well, at first in vans and from 1997 onwards in passenger cars: the A and later on the B-class models. Daimler has tried all storage options in combination with fuel cells, except for hydrides which could not provide the range that was needed. The divergence in storage methods is indicative of the pressure that the company felt from expected emissions regulations as well as of the open-minded research driven innovation strategy of the firm (van der Duin 2006). In terms of performance, the different models have typical top speeds of 145 km/h and their driving range has increased from 150 to 480 km. The biggest range is achieved by the liquid hydrogen model. However, here it shows that speed and range performance is not the only relevant criterion as the liquid hydrogen option was used only once. The same goes in that respect for on-board reformers. Both options provided longer range than high-pressure storage, but problems remained with energy-efficiency and the remaining (CO_2 and NOx) emissions which would not comply with expected regulations. The use of fuel cells provided higher energy-efficiencies as compared to ICE's, but the inefficiency of the storage systems minimized the overall efficiency gains. Gaseous hydrogen was used in vans at first and it was only in 2000 that an A-class was used as platform. Earlier gas cylinders stored hydrogen at 200 bar, but now 350 bar was used and the tanks were small enough to be fitted in a passenger car. The range was still limited at 200 km but it proved to be a start of Daimler's main trajectory with 5 models following. Including the 2009 B-class model of which 200 will be produced for large test programs in the US and Europe. The pressure is increased to 700 bar, giving the vehicles a 400 km range and enabling a higher top speed of 170 km/h.

GM/Opel

The prototype development strategy of GM and Opel can be characterized as overall broad, and as both sequential and parallel. GM/Opel has been a first mover once, in the FC/LH path and this is the earliest hydrogen vehicle in our data set. Three times it was an early follower and once it was a late follower. GM/Opel took part with 12 prototypes in 5 distinct paths during the whole time span from 1967 up to and including 2007. It switched paths sequentially two times in its earliest designs. In 2001 and 2004 it developed multiple designs simultaneously. In 2001 GM/Opel developed one in FC/LH and one FC/GH. And, in 2004 it released one prototype with the ICE/GH design and one with FC/GH. In most of the paths GM/Opel had one prototype (ICE/GH, ICE/MH, FC/Meth), in FC/LH it had three prototypes. GM/Opel left this path after 2001 and switched to FC/GH and produced 6 out of the 48 prototypes in that path.

GM's first hydrogen fuel cell vehicle, the Electrovan was presented in 1967 already. It could go 200 km with its supply of liquid hydrogen. For a publicity stunt, involving Jack Nicholson as driver, GM presented a Chevrolet hydrogen car in 1978 with an ICE and presumably a metal hydrides storage system. It was only in 1998 that GM took up hydrogen for real, with a modified EV1 (its notorious electric vehicle) with a methanol reformer and a fuel cell. In the same year, Opel presented the same configuration in its Sintra and Zafira models. In 2000 and 2001 two liquid hydrogen fuel cell cars were presented, both with 400 km ranges. In 2001 however, a gaseous hydrogen vehicle was also released, starting GM's dominant trajectory from there on. This vehicle only had a range of 130 km, but in later models this gradually increased to 480 km with increased hydrogen pressures. Among these fuel cell vehicles was the 2005 Sequel with a dedicated 'skateboard' chassis in which the full drivetrain was incorporated (McConnell 2007). The US developed prototypes are based on large SUV platforms, whereas the Opel prototypes are somewhat smaller multi-purpose vehicles. The only divergent model was a one-off hydrogen Hummer that was developed for Californian governor Schwarzenegger. The Hummer could only run 80 km on its supply of gaseous hydrogen. Currently, GM has 110 Equinox fuel cell/high pressure cars in a test and demonstration project.

Mazda

An example of a company that has a broad, diversified, and completely sequential strategy is Mazda. Mazda produced seven prototypes and started as a late follower of Daimler in the ICE/MH path. In this path Mazda produced a prototype in 1991, and in 1993. Mazda then switched to FC/MH and also here it produced 2 prototypes in 1997, and 1998. Next it moves in 2000 to FC/Meth, but this proved to be its last fuel cell vehicle and Mazda switched back to the ICE/Biv design. Mazda together with BMW is the only company that never produced a FC/GH prototype.

The main reason for Mazda's commitment to hydrogen combustion engines ever since, next to lower cost of combustion engines as compared to fuel cells, is its proprietary rotary engine. This engine design allows for more controlled combustion of hydrogen than in conventional engines. To compensate for the lower fuel efficiency of the combustion engine, Mazda has chosen bivalent engines (like BMW did as well). Nonetheless, its prototypes have never gone further than 230 km without refuelling. Mazda has started a lease program, but the number of cars was never revealed.

Toyota

Being rather active and seemingly dedicated firms, Toyota, Ford, Honda have all entered the prototyping race in phase II. Toyota produced 10 prototypes and has exclusively focused on fuel cells. This clear focus derives from the fact that fuel cells have been developed in-house from 1992 onwards. Toyota opened up the FC/MH path, and in parallel it produced 2 FC/Meth prototypes. Toyota first presented a hydrogen prototype in 1996 and its fuel cell was powered from a metal hydrides storage system, the first in the industry. The following year, the same platform was modified and could then run on reformed methanol, improving the vehicle's range from 175 km to 500 km. Together with Daimler it was also the pioneer for this design. In the year 2001 it strikingly presents three different prototypes, next to the metal hydrides models, it also showed an on-board reformer (which would be its last) and its first prototype with a 250 bar gaseous system. The latter could achieve a 250 km range. While reformers fell out of favour due to emission standards, metal hydrides proved incapable of increasing range. Toyota did announce a doubling of storage capacity from 1.5 to 3 percent hydrogen-to-system weight ratio, but further increases proved impossible without breakthrough materials. From there on Toyota has stuck to the high-pressure option and ranges were increased to 500 km with increased hydrogen pressures. Top speeds remained roughly the same at about 150 km/h.
Toyota's platforms for its hydrogen activities have consistently been their SUV/crossover models, from the RAV4 to the Highlander. The size of the vehicles has allowed for the size of the storage systems. Recently, Toyota announced a test program with 100 vehicles in the US.

Ford

A first glance at the trajectories followed by Ford reveals two points: first it started relatively late with HPC prototypes (only in 1999) and second, it explored a wide range of designs. Until 2007 Ford released 11 prototypes. Its strategy evolved into a broad diversified portfolio spread across four different paths including parallel development of ICE and FC prototypes. In that sense, Ford's strategy has some resemblance to Daimler's approach, be it at lower speed and intensity.
Both combustion engines and fuel cells are exhibited in respectively 2006 and 2007. The platforms have also varied to a large extent for both conversion options, from the electric vehicle start-up Th!nk, with which Ford was shortly partnering, to SUV type models such as the Explorer and Edge. Apart from two vehicles in 2000, which had an on-board reformer, Ford has shown a strong preference for high-pressure storage. Whereas in early models 250 bar was used, Ford moved to 350 and later 700 bar storage systems. The latter provided their 2006 SUV fuel cell type a 560 km range, but in 2007 Ford returned to 350 bar which set back the range of both fuel cell SUV's of that year to 360 and 500 km. Clearly, range was not the only criterion used and like other manufacturers Ford focused on fuel cell performance and overall efficiency of drivetrain as well. In its ICE prototypes, ranges vary as well. Top speeds are only scarcely communicated and never exceed 140 km/h. Ford did however set a speed record for hydrogen fuelled vehicles at 333 km/h, but this was merely a publicity item. Ford was early with hydrogen test fleets such as a 30 unit program in 2001 and another fleet of 30 HPCs in 2006.

Honda

Honda is the third company that entered the HPC arena in phase II. Honda developed a highly focused strategy and clearly has a preference for the FC/GH path in which it produced 7 prototypes. In 1999 Honda introduced one prototype in FC/MH and FC/Meth each. This makes Honda's strategy the deepest in the industry in the sense that all its prototypes are in FC, and the largest share (7 out of 9) of prototypes is produced within the FC/GH path. The

Other firms

The group of companies with 5 or less HPC prototypes consists of Suzuki, Fiat, Nissan, Peugeot, Hyundai, Mitsubishi, and VW/Audi. They entered relatively late in hydrogen vehicles either in the last part of phase II, but mostly in phase III.

The thickening of the FC/GH path is explained mainly by the fact that the majority of Japanese and Asian HPC producers Toyota, Honda, Mitsubishi, Nissan and Hyundai exited the FC/MH path and FC/Meth path and entered the FC/GH path. On top of that also the car companies that produced smaller numbers of HPC prototypes and were mostly not early followers, but merely late followers, like VW/Audi, Hyundai, Peugeot, Nissan, Fiat, Suzuki, always released FC/GH prototypes and some of them the larger share (VW/Audi: 3:4; Hyundai 4:5; Peugeot 2:2; Nissan 3:5; Fiat 2:3; Suzuki 2:2).

4.7 Conclusions

Competition between technological options is not confined to the market. In the end, this pre-market competition might even result in the selection of a dominant design. That design then, is not so much dominant in the market, as the market is not entered yet, but it is dominant in the prototyping phase and it is the design that will be put forward by an industry to challenge the existing dominant design.

In our study we traced the competition in the pre-market phase in the case of hydrogen passenger cars. One design has emerged as the dominant prototype design throughout the industry: the fuel cell vehicle with high-pressure hydrogen storage. In the absence of market forces, it is a combination of current and expected technological performance characteristics, anticipated regulations and strategic manoeuvring of the firms that guides the selection of the emerging dominant design. Before this design became dominant, a wide variety of options was developed and tested. One of the major rationales for the industry to work on hydrogen vehicles and to explore such a wide variety of designs, has been regulatory pressure from governments, such as the Californian standards for zero-emission vehicles and the announced EU regulations on CO_2 for 2012. Another factor is the expected rise in fuel costs, making that fuel efficiency will be of greater concern to future customers than it is today. Cost of ownership and especially cost of use will become much more important in the future than it is today, according to manufacturers.

These pressures presented the challenge of developing a vehicle that performs in accordance with customer preferences and complies with the expected regulations. A complicating factor was, and still is, that the fact that there is no single performance measure and that the different performance characteristics constrain each other: with greater driving range comes less top speed for instance and those vehicles that had the greatest driving range did not comply with CO_2 emission standards. From the start of hydrogen vehicle development, it was not clear what design would fit best with the complex set of performance measures, regulations and customer preferences. We have identified eight main paths that were explored throughout the industry and for each of those paths the individual firms must have had positive expectations of further progress. In other words, the different paths that were explored did not deliver the desired performance on all relevant measures and it were mainly high technological expectations that kept the firms on those paths. Over time, some of the paths were abandoned because of changing regulation or because it became clear that further progress was unlike with the given design.

We have shown in our analysis that mimicking behaviour by a large number of firms must have played a role in the process of variation and selection. Only seven firms can be said to be first movers, the rest has acted as followers. From those seven firms, BMW, Daimler and GM have been the most prominent leaders. The paths that they have opened were promising to themselves and in most cases to other firms as well, the followers have not only mimicked the design but they have adopted the positive expectations as well. BMW is an exception to this, while BMW clearly had high and stable expectations of the hydrogen combustion engine, these expectations were not shared by other firms, with only Mazda exploring this option in the majority of its prototypes. It was the path that was opened by Daimler that did attract a lot of followers. It was able to gain dominance, we argue, because it was this design that showed most progress and remained promising. That is, the FC/GH design showed progress terms of driving range and energy efficiency and the expectations were strengthened by a number of demonstration projects with tens or hundreds of vehicles. These projects have signalled the dedication of those firms with respect to that design and this has helped to transform this promising design into a truly feasible option.

These technological and strategic factors have co-evolved and reinforced each other for two reasons. First of all, there is an incentive for agreement on the best design before market entry. The (technologically) best performing design can only succeed when the majority of firms adopt it. This incentive for agreement on the design before market entry is presented by network externalities and economies of scale. For instance, there is the need to build up an infrastructure for the refuelling of the vehicles. Strong commitment on the part of BMW to a liquid hydrogen vehicle will only result in market success if other firms adopt this option as well and a liquid hydrogen infrastructure is build up as a result. Second, those firms that are most active in the development of hydrogen passenger cars give the strongest signals about their expectations of their designs and they produce the greatest numbers of prototypes and engage in demonstration projects with their fleets. For other firms, the followers, this is reason to adopt those promising designs as well. These followers do not explore the full variety of paths but in order not to miss out, they develop a small number of models in the path that is surrounded by collectively held positive expectations. Their conformity amplifies the expectations held on a certain configuration.

The extent to which the pre-market dominant prototype design will actually be dominant once the market is entered depends on the positive feedback that is associated with that design. In the market, dominant designs benefit from economies of scale, standardization and network externalities. This is currently not the case for hydrogen vehicles and the industry could still opt for another design if desired. However, hydrogen infrastructures are also being built up and are designed to deliver high-pressure gaseous hydrogen. Diverging designs with different storage technologies will not profit from this infrastructure and would therefore face an extra barrier.

Apart from the refuelling issue, individual firms might switch from one design to another, as our data showed in some occasions. But, the industry as a whole does seem locked-in in the trajectory that has become dominant. We conclude that prototyping may result in a dominant design before market forces are at play. Tracing the configuration of prototypes appears to be helpful to untangle the dynamics of variation and selection and of technological trajectories before they enter the market. A study of prototypes, therefore provide an alternative to the ex-post conclusions that have been drawn in literature so far.

Acknowledgements

We thank Floris Prager for his contributions to the dataset of prototypes, and Jochen Markard, Roald Suurs and Carolina Castaldi for their comments on draft versions.

5. Hydrogen patent portfolios

5.1 Introduction[18]

Pressure is mounting on the automotive industry to develop clean and affordable alternatives to the ubiquitous gasoline car. Pressure is felt through consumer demand for cars with higher fuel efficiencies and regulation which either demands lower emissions or vehicles with no emissions at all. The development of low-emission vehicles and zero-emission vehicles has a long history and has been studied by scholars intensively. A particularly interesting strand of literature deals with the patent portfolios of car manufacturers. Patents are taken as an indicator of the variety of technological options that are developed by firms. In this paper, the focus is on one of the options specifically: the hydrogen vehicle. The aim is to uncover the dynamics of variety of technological options for the hydrogen vehicle. The hydrogen vehicle as a whole can be regarded as a technological system in which a number of technological components are brought together. Two key components are often identified. The first and seemingly the most challenging component is the on-board storage of hydrogen. Storage systems need to be able to store enough hydrogen in a safe and energy efficient way, to provide the vehicle with an acceptable range without refuelling. The second component is the conversion of hydrogen to power. When looking at hydrogen prototype vehicles that have been developed over the years, an impression is formed that high-pressure gaseous hydrogen in combination with a PEM fuel cell is the design favoured by the industry (Bakker et al. 2010).

As this paper will show, car manufacturers' patent portfolios show rather different dynamics: a diverse set of storage options is still being explored. Not only is this of interest to innovation studies scholars who are interested in the relation between patents and prototypes as indicators of innovation processes. It could have implications for the commercialization of hydrogen vehicles as well. First, the

18 This chapter is published as: Bakker, S. (2010) Hydrogen patent portfolios in the automotive industry - The search for promising storage methods, *International Journal of Hydrogen Energy*, vol.35, no.13, 6784-6793

continuing exploration of design options suggests that high pressure storage is not entirely satisfactory from the manufacturers' perspective. And second, the build-up of a hydrogen infrastructure is in part dependant on standardized fuelling technologies and protocols. As each on-board storage system requires specific refuelling technology and protocols (Maus et al 2008), standardization to some extent of on-board storage systems seems vital to the build-up of a hydrogen infrastructure.

This paper is structured as follows: first the notion of evolutionary dynamics in innovation processes that rely on variation and selection of technological options is elaborated. Second, earlier studies on patents in the automotive industry are discussed and from that the research question and hypotheses are developed. Third, in the results section, it is shown what technologies have been patented by individual manufacturers and what industry-wide trends this has produced. Finally, these trends are compared in terms of variety with hydrogen prototype vehicles that have been presented.

5.2 Variation and selection of technological options

Technological development is often described as a continuing evolutionary process of variation, selection and retention (Dosi and Nelson 1994, Arthur 1989, Nelson and Winter 1977). Different technologies are seen as variations, while the market, in a broad sense, is their selection environment. Successful innovations are assumed to be the fittest in their given markets. In the selection environment, choices are made between different variations at the level of competing individual technologies and, eventually, at the level of competing sociotechnical systems (Geels 2006). The evolutionary process of variation and selection thus assumes competition, not only between the technologies or systems, but also between the actors advancing them. While the evolutionary perspective has proven to be fertile and has led to important further insights and new policy inspiration (Geels 2006, Suurs et al 2009), it also raises the question of how variation and selection are related. A strict evolutionary metaphor for technological change must be inappropriate, since variations are not blind and selection is not fully independent. And also, competition between different technological variations already takes place long before any market is entered. The *quasi*-evolutionary model (van den Belt and Rip 1987, Schot 1992, Rip et al. 1995) stresses the connection between variation and selection through the anticipation and strategies of various actors. Actors anticipate the selection environment because they have some understanding of its future demands, for instance by extrapolating ongoing improvements. Actors will also seek to modify selection environments (Bakker et al 2011) by voicing expectations or by forging strategic alliances. The quasi-evolutionary approach, thus, provides us with a model of technological development and competition that is not dependent on spontaneous and blind variation of technologies alone, but one that relies on agency and thus on guided search and selection activities. Much of the anticipated selection environment for emerging technologies is based on expected levels of performance that must be met by the technology: the 'aspiration level' (Lant 1992). To bridge the gap between actual performance and aspired levels of performance, firms engage in 'problematic search' (Levinthal and March 1981). That is, different technological variations are developed and tested to achieve the aspired levels. Note that this is different from pursuing progress on one specific technology alone. Such a portfolio approach in innovation has also been approached as a process of exploration of different options (March 1991). In successful innovation trajectories, the process of exploration is followed by positive selection of the best performing option which is then exploited: exploration and exploitation.

For hydrogen vehicles, the innovation process of technological components is still in the exploration phase. This is most clearly visible in the on-board hydrogen storage component: the hydrogen vehicle is a promising option, but the performance levels of storage options are far from aspired levels and this opens up the search process for storage options that can meet those levels. In other words, there is a lot of exploration and no exploitation yet. In the next section, an operational definition is provided of the notion of variety in exploration processes and the use of patent portfolios as indicators of the exploration process and ultimately as indicators of distance to commercialization.

5.3 Patents as indicator of innovation portfolios

Patents are a well-known method of studying innovation (Archibugi and Planta 1996). Two general aims can be distinguished in the literature. The first is the rate of innovation of firms, sectors, countries, etc. The number of patents is then taken as an output measure in relation to, for instance, R&D investments (Pavitt 1982, Watanabe et al 2001, Seymour et al 2007) or in relation to key inventors in a field such as fuel cells (Pilkington et al 2009). The second is the direction of innovation, the issue dealt with in this paper. To gauge the direction(s) of innovation in the car industry, the sector and type of firm are equal for all. Country or regional specificities do play a role and this will be discussed shortly in relation to the research methodology.

Patenting activity in the car industry has been studied quite extensively in relation to the industry's quest for low or zero-emission vehicles (Oltra and Saint Jean 2009, Pilkington et al 2002, Pilkington 2004, Frenken et al 2004, Hekkert and Van den Hoed 2004, van den Hoed 2007, Hekkert et al 2005). A general notion that can be taken from these studies is that there is indeed variety in the options that are pursued. The car industry manages the uncertainty related to car designs of the future by maintaining a wide portfolio of options. The exploration process is thus typically one of high variety in the technologies that are pursued. The conventional car design is still subject to many improvements in terms of fuel efficiency and emission reductions and, especially in Europe, this seems to be a major aim of manufacturers (Oltra and Saint Jean 2009). The development and commercialization of hybrids is ongoing and so is the development of plug-in hybrids. And, although they may still be at a R&D and testing stage, pure battery electric and hydrogen vehicles are also heavily studied and patented.

On a more abstract level, two complementary propositions on technological variety stand out from this body of literature. The first is that variety is desirable in an ongoing search for optimal solutions (Frenken et al 2004). It is desirable because prematurely converging to one option in the development process might lead to a lock-in in the chosen direction (Alkemade et al 2009). That is, when firms switch from exploration to exploitation, the choice for that specific direction may turn out to be irreversible due to high sunk investments, and from positive feedbacks from economies of scale and network externalities such as infrastructures. Other directions might have led to more optimal solutions in the long run, but are no longer viable because the chosen solution has become too dominant (Abernathy and Utterback 1978, Murmann and Frenken 2006). Patenting dynamics in Germany for instance, showed a potential for a lock-in in hydrocarbon reforming technologies (Hekkert et al 2005), while from an emissions-reduction point of view this is not the most desirable option.

The second proposition is that a narrowing of patent portfolios is indicative of a short distance to commercialization and market entry (Pilkington 2004). That is, when firms start to patent similar technologies they seemingly agree on what will work best and what is commercially viable and thus presents the option that is to be exploited. These two propositions are complementary to the extent that they both suggest that convergence within innovation portfolios (i.e. less variety in the exploration phase) is indicative of the actual positive selection of the technology to be commercialized and thus of the solution that is deemed most viable. In relation to the commercialization of hydrogen vehicles and the build-up of a hydrogen refuelling infrastructure this paper aims to answer the question:

Do patenting activities with regard to hydrogen vehicles show convergence within portfolios and what are the favoured technological components?

In order to answer this question two hypotheses are formulated. *The first hypothesis (H1) is that car manufacturers have indeed maintained a portfolio of technological options, rather than developing only one single option.* With such technology portfolios, some form of portfolio management is necessary. Resources in the firm are limited and no firm can pursue all of the possible options simultaneously. Firms may add new technologies to their portfolios and may also drop other technologies from their portfolios when they are no longer deemed viable. Portfolio management of is thus effectively a quasi-evolutionary process of variation and selection of technological options.

From an earlier analysis of hydrogen prototype vehicles (Bakker et al. 2010), which will be discussed in more detail in the methodology section, it follows that a dominant design is emerging for hydrogen vehicles: the portfolio of technological components in hydrogen prototypes is narrowing on a combination of fuel cell and gaseous hydrogen storage. Following the propositions described above, the narrowing of portfolios in the prototypes may hint at positive selection of a preferred option within the industry and could also be indicative of a move towards commercialization. Assuming that prototypes and patents show similar dynamics (i.e. when roughly the same options are visible in both prototypes and patents), one expects to see the same pattern of convergence in the patent portfolios as was seen in the prototypes. *The second hypothesis (H2) is thus that industry-wide patent portfolios converge to the fuel cell and high-pressure hydrogen storage design.*

5.4 Technological options for hydrogen vehicles

No commercial hydrogen vehicle is available today and no one can tell for sure whether there will ever be one. Still, car manufacturers are developing the technologies and they consider the hydrogen vehicle to be a serious contender in the race for the fuel of the future (van den Hoed 2005, Sandy Thomas 2009). Whether or not hydrogen vehicles will ever see market introduction depends on technological achievements in terms of (well-to-wheel) energy efficiencies, cost price reductions, consumer preferences, path dependencies in the automotive industry and also the willingness of other actors, such as governments and fuel suppliers, to deploy a hydrogen infrastructure.

One aspect of this stage of development is that the design of hydrogen vehicles is still very much open: there is not a single hydrogen vision (McDowall and Eames 2006) and there is not a single hydrogen car design that is fully developed and unchallenged. Hydrogen can be stored and utilized using different technologies and a dominant design of the hydrogen car has not yet been established in the market. In this paper, the focus is on the technological options for the two main components in the hydrogen vehicle. These two are essential to make a hydrogen car competitive with existing designs and future competitors such as plug-in hybrids. The first is the conversion of hydrogen into power, which can be done using a combustion engine or a fuel cell. The second is the method for storing hydrogen on-board the vehicle for which a multitude of options are explored. In the following, the different options and their major advantages and challenges are discussed.

Hydrogen conversion options

Because of its high efficiency, the fuel cell is often seen as one of the main drivers for hydrogen as a fuel of the future (Eisler 2009). The vast majority of automotive fuel cell applications rely on PEM fuel cells. Fuel cells have proven to be highly efficient in converting hydrogen to power. However, a number of challenges remain to be solved. The first and foremost issue is the production cost of fuel cells, for a large part due to the platinum catalyst that is needed. Further issues that have to be dealt with include, amongst others, the lifetime of the cells and its reliability in extreme conditions such as freeze-start conditions (Frenette and Forthoffer 2009).

The hydrogen internal combustion engine (ICE) is still considered by a number of firms, most notably by BMW and Mazda, as the less costly and better understood alternative to fuel cells. The ICE's low energy efficiency does however pose problems in terms of well-to-wheel efficiencies, which would not be favourable over conventional gasoline vehicles. Still, ICE's could be used as a transitional technology on the way to fuel cell vehicles and they could possibly trigger the build-up of a hydrogen infrastructure even before fuel cells are competitive.

Hydrogen storage options

On-board storage of hydrogen is still one of the biggest challenges for hydrogen vehicles (Sakintuna et al 2007, Felderhoff et al 2007). While the fuel cell is often seen as a true enabler (creating an opportunity) of the hydrogen vision, storage is seen as a problem. Because of the low volumetric energy density of hydrogen as a gas under ambient conditions, it is a challenge to take enough hydrogen on board to allow for an acceptable vehicle range without refuelling. Physically, the volumetric density can be increased by pressurizing or liquefying the gas. Both options require significant amounts of energy, giving energy losses up to 20% for compression and about 30% for liquefying (Department of Energy 2002). On top of that, high pressure gaseous hydrogen (up to 700 bar) is considered a potential safety hazard. Liquefied hydrogen furthermore suffers losses due to so-called boil-off: it is impossible to prevent any hydrogen from evaporating and the resulting gas has to be released.

As an alternative, even more challenging options have been proposed and investigated. Most attention is paid to storage in solid materials and especially metal hydrides. Here, hydrogen gas is fed to a tank containing a metal powder and is absorbed as hydrogen atoms in the metal's atomic lattice to form a metal hydride. In metal hydrides, hydrogen can be stored with a higher volumetric density than for instance liquid hydrogen. The main disadvantage however is in the weight of the storage alloys. Also the rates of absorption and desorption (increasing refuelling time) and operating temperatures are still problematic. Other competition for gaseous and liquid storage has come from methanol as a carrier of chemically bonded hydrogen. Methanol is reformed to gaseous hydrogen and carbon dioxide with an on-board reformer. Almost all manufacturers have experimented with on-board reformers in prototype vehicles, but even though long ranges could be achieved all firms have shifted away from this option in their prototypes.

Less visible in prototypes but nonetheless under consideration are storage options such as carbon/graphite (nano-)materials in which hydrogen can be adsorbed, storage in chemical hydrides (bonding the hydrogen to a liquid chemical substance such as ammonia or hydrazine), and rather exotic methods such as clathrates (ice-like structures capturing the hydrogen). These solutions however are at this point not practically usable and not yet used in prototypes.

In the analysis of patented technologies for both conversion and storage, two conversion options and five of the most patented storage options are selected (listed in Table 5.1). In the discussion of individual firms some of the other options are discussed when appropriate. All of these storage options can be used in combination with both fuel cells and combustion engines, except for on-board reforming of hydrocarbon. For the other combinations there is nothing to suggest that either one of the conversion options rules out any of the storage options.

Table 5.1 Main technological options for hydrogen vehicle technologies

	Conversion	**Storage**
Technological options	Fuel Cell	Gaseous hydrogen
	ICE	Liquid hydrogen
		Metal Hydrides
		On-board reforming
		Carbon materials

5.5 Methodology

For the analysis of hydrogen patents in the automotive industry, twelve car manufacturers were selected: Toyota, Honda, Nissan, Mitsubishi, Hyundai, Daimler, BMW, Volkswagen, General Motors, Ford, Renault and Peugeot. The selection of manufacturers is the same as that made by Oltra and Saint Jean (2009), with the addition of BMW because of its prominent position in hydrogen vehicle development. Patents were retrieved from the European Patent Office online database: Esp@cenet. The Esp@cenet database contains patents of more than 70 countries[19] and can be searched using patent classifications as well as using search terms[20]. In order to minimize any bias in the search method, the search term "hydrogen"[21] was used. The search term was combined with the car manufacturers' names in the applicant field. The study covers the 1990-2009 timeframe and patents were retrieved year by year. The abstracts of the patents were studied and relevant patents were assigned to the pre-defined categories of Table 5.1. For most firms the search term "hydrogen" was used on both the title and the abstract category in the search engine. However, for four of the Japanese manufacturers (Toyota, Honda, Nissan, and Mitsubishi), searching in both title and abstract resulted in too many hits (>1000) to go through individually[22]. In order to limit those patent sets to a size comparable with US and European manufacturers, only the patent title was used in the search process. Searching for hydrogen in the title field alone will not deliver all significant patents. However, this does not create any significant bias in the dataset as compared to patents that would be found by searching title and abstract. That is, the storage options are all specific to hydrogen and there is no ground to assume that the Japanese manufacturers would use different terms in their patent titles.

The process of studying patents and assigning them to the pre-defined categories is not straightforward. Many patents are written in rather general terms, as they are designed to protect knowledge as widely as possible. Especially when only the abstract and title is available, this can pose some problems[23]. For instance, in the case of reforming technologies, a patent can be about large-scale stationary hydrogen production as well as about on-board reforming. In that case, those patents were counted as on-board reforming patents because centralized hydrogen production is not the core-business of car manufacturers and also because methanol is often mentioned as one of the possible hydrocarbons to be reformed. Hydrogen purification patents posed another issue. These do not fit the categories as

19 www.espacenet.com

20 Hydrogen technologies are not well defined in the patent classification system and searching for patents by their classifications is rather problematic. The very fact that these classifications are not (yet) well-defined indicates that the technology is rather far from commercialization.

21 More specific search terms generated only fractions of the actual numbers of relevant patents and the use of those terms (such as "gaseous hydrogen" or "metal hydride" is very much dependent on the specific use of terms by the individual patent applicants (i.e. car manufacturers).

22 One explanation for these sizeable patent sets is the fact that patenting is less expensive in Japan as compared to the US and EU (Oltra and Saint Jean 2009). Another is that Japanese patent law and culture favour narrowly defined patent applications (Maskus and McDaniel 1999).

23 Especially for the Asian patents, often only a translated abstract or even a title was available.

such, but when they referred explicitly for use in combination with fuel cells, they were assigned to the fuel cell category as an integral part of a hydrogen fuel cell system.

The analysis of the patent portfolios is done first for each of the car manufacturers in order to deal with the first hypothesis. Graphs for each of the manufacturers, depicting the patents on each of the technological options throughout the timeframe, were constructed to analyze the basic dynamics. The same was done for industry wide trends in patented technologies.

To analyze whether or not the patent portfolios are converging towards a single option, the second hypothesis, one needs a measure for the variety of technological options that are considered. Entropy is one such measure, as a conceptual metaphor, and it can be calculated from the shares of the technological options in the patent portfolios (Frenken et al 1999, Frenken et al 2004). Entropy (H) is then defined as:

$$H = -\sum_{i=1}^{m} p_i \ln p_i$$

For a set of m technological options (i) for a specific function in the hydrogen vehicle, (with $i = 1,..,m$), p_i is the share of technological option i in a patent portfolio. When the patent portfolio consists of only one option ($p_i = 1$), entropy is at its lowest and H = 0. A greater number of technological options and more evenly distributed shares in the patent portfolio make for a higher entropy score. Entropy is calculated per year and H is thus the entropy in the portfolio of patents that were granted in a given year. As the second hypothesis deals with the relation between patent and prototype portfolios, entropy is also calculated for prototypes. Each year's prototypes are taken as that year's industry-wide portfolio. For hydrogen prototypes, data from an earlier study is used (Bakker et al. 2010). For that study, a database of 224 hydrogen prototype cars was compiled. The data were gathered through an online search, using mainly websites dedicated to hydrogen vehicles, car manufacturers' websites and general car news sites. Additionally, this search was supported by already existing overviews of hydrogen models, by visits to several car shows (Amsterdam, Geneva) and validated by industry researchers. Buses, trucks, and utility vehicles were excluded from the database. Several technological specifications were included in the database: brand, year, storage method, amount of hydrogen stored, conversion technology used, manufacturer of the fuel cell or engine, range, maximum speed. For the purpose of the analysis presented in this paper, only those prototypes that were presented to the public from 1990 onwards are used. In the comparison between the patent and prototype portfolios, only the on-board hydrogen storage component is taken into account.

5.6 Results

The results of the patent analysis are presented in three subsections. First, the patent portfolios and dynamics of variation and selection for each of the individual firms are discussed. Second, the major trends throughout the industry are shown. And third, the dynamics in terms of the entropy of the industry's patent portfolio vis-à-vis hydrogen prototype vehicles are presented.

Table 5.2: Overview of patents in the full dataset from 1990 to 2009. Ordered by manufacturers and technological options: Fuel Cell (FC), Internal Combustion Engine (ICE), Gaseous Hydrogen (GH), Liquid Hydrogen (LH), Metal Hydrides (MH), On-board Hydrocarbon reformer (Reforming) and Carbon materials (Carbon) *for these firms only patent titles were searched for, for the other firms title and abstract were used.

	Conversion		On-board storage					
	FC	**ICE**	**GH**	**LH**	**MH**	**Reforming**	**Carbon**	**total**
Toyota*	121	74	37	15	243	113	22	625
Honda*	40	2	26	3	79	64	8	222
Nissan*	32	0	6	0	20	35	24	117
Mitsubishi*	34	4	7	6	64	146	7	268
Hyundai	77	14	6	0	8	4	2	111
Daimler	58	6	6	8	3	41	0	122
BMW	6	21	2	34	6	13	0	82
Volkswagen	23	2	3	0	1	13	0	42
General Motors	114	1	14	10	27	69	1	236
Ford	24	18	4	0	2	4	0	52
Renault	50	0	0	1	1	41	0	93
Peugeot	20	0	3	0	0	2	0	25
total	599	142	114	77	454	545	64	1995

Table 5.2 provides an overview of the patents in the dataset. A first glance at the data reveals that fuel cells and fuel cell systems are patented four times more often than hydrogen combustion engines. Storage patents show more variety and more complex dynamics over time. In the following, the patent portfolios of individual firms are discussed in order to gain more insight into each firm's portfolio management practices. Graphs of each firm are provided in a separate frame (Figure 5.1).

Toyota

Toyota holds the largest number of hydrogen-related patents in the car industry. It holds patents on both conversion technologies, with a strong emphasis on fuel cells. Noteworthy here is that Toyota's attention for ICE's came in two periods, one in the first half of the 1990s and the second from 2004 till 2008. In terms of hydrogen storage, Toyota holds patents on all options, but the patents concerning storage alloys stand out. Especially in the period 1997-2004, the Toyota data show a peak for this option[24]. However, after this peak, interest in gaseous (since 2004) and liquid hydrogen (from 2007) takes over. In between these peaks, Toyota has also taken an interest in methanol (and other

24 In 2005 there was a patent for high pressure hydrogen in a storage alloy. In such a case, the patent is counted in both categories. This is a rare case however.

hydrocarbons) reforming technology. Hydrogen storage in carbon structures has also been patented by Toyota mainly between 2001 and 2004. Other options that are mentioned in the patents include hydrazine, amides and ammonia as chemical storage options.

Nissan

Nissan clearly focused on fuel cells rather than hydrogen combustion engines: on the latter no patents were found. Except for liquid storage it has worked on all storage options. Most of Nissan's storage patents relate to methanol reforming. After the reforming peak in patents, metal hydrides are more frequently patented. This indicates a revival of metal hydrides as storage materials as they were already patented in 1995 and even in 1991 for their thermal use in a defrosting unit. Nissan's attention on storage in carbon structures was at its peak in between the reforming and the metal hydride phase.

Honda

Honda clearly has a preference for fuel cells over combustion engines, be it however only since the turn of the millennium. With regard to storage, it has explored all options, especially between 2000 and 2006. Most striking are the subsequent peaks in metal hydrides and reforming patents and the following rise of gaseous storage. This suggests that metal hydrides were seen as promising but did not meet expectations and were subsequently dropped in favour of reforming which in turn was followed by gaseous storage. Liquid and carbon-based storage have only been patented in relatively small numbers. Honda holds some patents that relate to infrastructural technologies such as fuelling stations and hydrogen generation through electrolysis (including direct solar hydrogen generation) and household natural gas reforming units[25].

Mitsubishi

Mitsubishi already held patents on fuel cells in the early 1990s, earlier than for instance Nissan or Honda, and Mitsubishi has favoured these over ICE technology. Furthermore, in the early 1990s it was working on metal hydrides and methanol reforming. Peaks in these patents can be seen well before the turn of the millennium. While metal hydrides patents are less prominent since the turn of the millennium, reforming technologies see a new peak around 2004. Gaseous, liquid and carbon are the subject of fewer patents and these can only be found since 2002. Like Honda, Mitsubishi holds a number of hydrogen production patents. This could indicate that it plans to develop hydrogen infrastructures to refuel its vehicles.

Hyundai

Hyundai started relatively late with its R&D on hydrogen technologies. Its first patents are granted in 1999, starting with metal hydrides. Hyundai patented storage technologies before conversion technologies. When it did so, it started with ICE patents, but it quickly switched to fuel cell technology.

25 These household reformers are said to be used by lease customers of Honda's FCX Clarity hydrogen vehicle to fuel their (test) cars at home.

Since 2003 it has applied for patents on fuel cells only. On storage, Hyundai holds patents on gaseous storage, metal hydrides and on-board hydrocarbon reforming.

Daimler

Daimler is known as one of the industry leaders in hydrogen technologies and its patents confirm this. From the 1990s onwards, Daimler holds hydrogen-related patents both in propulsion and storage technologies. Up and until 2004, fuel cells and ICEs[26] have been in Daimler's portfolio, since then it has only filed fuel cell patents. In its work on storage technologies, Daimler has also maintained a wide range of options, with methanol reforming patents showing the most promising peak in the second half of the 1990s. Whereas in the 1990s liquid hydrogen was patented, in later years most attention seems to have been given to gaseous hydrogen storage and some metal hydrides.

BMW

BMW has always voiced a strong preference for combustion engines in relation to hydrogen. The main reason for this is the company's customer base which prefers powerful cars and besides that, BMW regards the ICE as a less costly and more durable option than the fuel cell. This preference is reflected in the patent portfolio, but the company holds six FC patents as well. Most probably, these are aimed at auxiliary power generation for on-board electricity needs rather than for propulsion purposes. From the storage patents, a preference for liquid storage stands out, even though high pressure cylinders and metal hydrides have also been patented. Overall, BMW patents peak around 2006.

VW

Volkswagen is among the firms with smaller patent portfolios. With the exception of two ICE patents in the early phase of it hydrogen patenting, Volkswagen has focused on FCs. Its storage portfolio is also rather limited in scope: on-board reforming and gaseous hydrogen and one rather late metal hydride patent have been filed.

General Motors

General Motors started early in the 1990s with patenting hydrogen technologies. In those early days, the focus was on fuel cells and on-board hydrocarbon reforming. In 2004, one ICE patent was added and since then GM's attention on storage technologies has widened to include other options including one carbon and a number of amide patents.

Ford

In contrast to the other firms, Ford's patents show no clear preference for either fuel cells or ICEs: it holds patents on both options up until 2009. As for storage technologies, the small number of patents

26 One of the ICE patents deals with a so-called rotary piston engine, a design that was also considered by Mazda in its conventional cars as well as its hydrogen prototypes.

held by Ford deal with metal hydrides and on-board reforming at first, but have been followed by gaseous storage patents.

Renault

Renault does show a portfolio approach like many of the other manufacturers, but with a limited number of patents in total. Its conversion patents deal exclusively with fuel cells and for storage all but two patents deal with on-board reforming. These two are on liquid hydrogen and metal hydrides.

Peugeot

Like Renault, Peugeot has a rather narrow portfolio of hydrogen patents with a strong focus on fuel cell technology. On storage however, Peugeot has focused more on gaseous storage and only little attention (two patents) was paid to on-board reforming. Other storage options have not been patented.

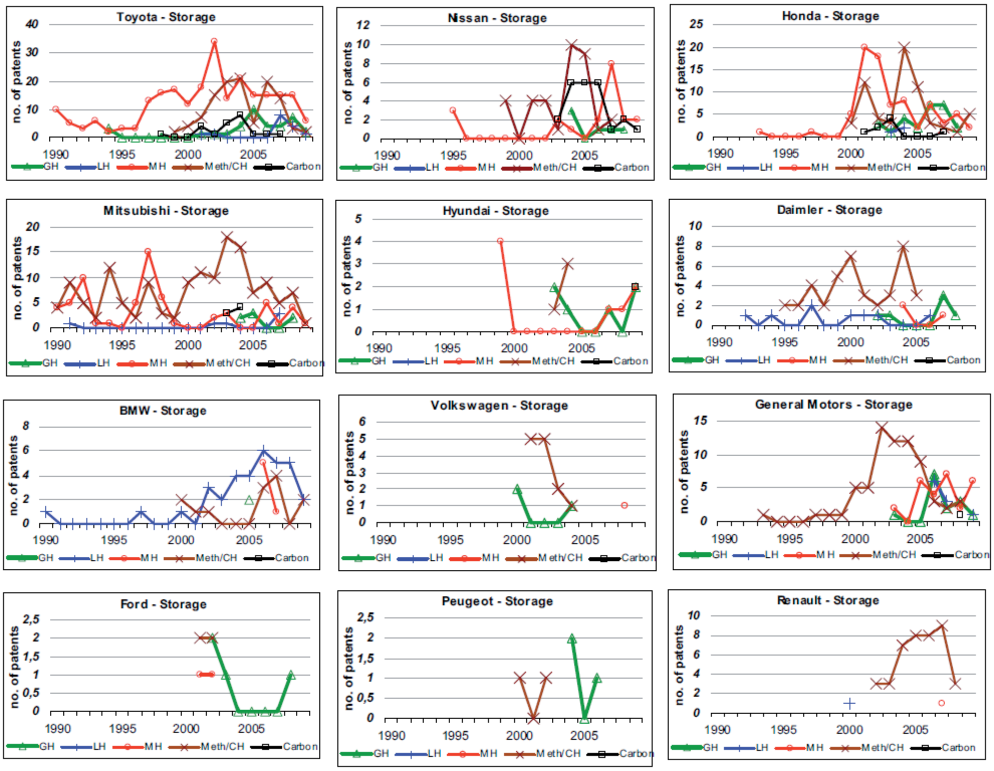

Figure 5.1 Hydrogen storage portfolios of the individual car manufacturers 1990-2009

General trends

Industry-wide conversion patent trends indicate that Ford, Toyota and BMW are the only manufacturers that have patented ICEs in the last five years and Mitsubishi was granted one patent in 2005 on a bivalent hydrogen/gasoline combustion engine. With the exception of BMW, these firms hold larger portfolios of fuel cell patents than on ICEs within the 2005–2009 timeframe. For conversion technologies, it is therefore clear that the industry converges on the use of fuel cells in hydrogen vehicles.

Trends in storage technologies show more diversity and more dramatic dynamics. These trends are plotted in Figure 5.2. The figure shows for each year, the absolute numbers of patents throughout the industry. Overall storage patenting activity peaked roughly from 2002 to 2004, which corresponds with the high expectations for hydrogen in those years.

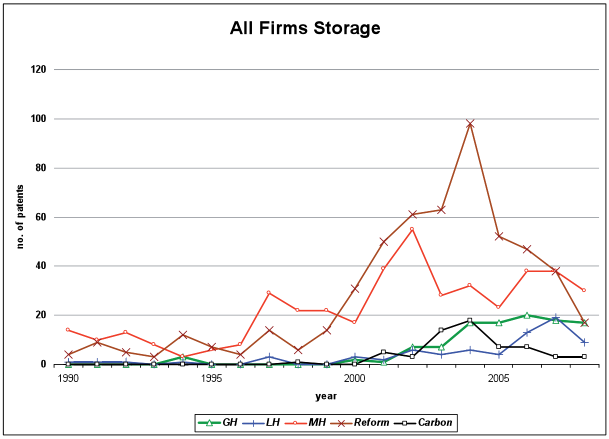

Figure 5.2: Industry wide patent trends for each storage option

In the early 1990s, metal hydrides, methanol reforming, and to a lesser extent liquid hydrogen are the most patented technologies. Reforming patents peak in the early 2000s, up to almost 45% of the patents sets in 2001. From then on, reforming receives less attention but remains a sizeable portion of the year-to-year sets. The decreasing numbers of reforming patents coincide with the DOE decision to give it a no-go and end the funding for on-board reforming R&D (DOE 2004). The DOE decided so partly because the car industry had indicated that it saw no future for on-board reforming. Metal hydrides show a more stable development, apart from a downward spike in 1994 and an upward spike in 1998. The fluctuations in liquid hydrogen patents can be explained by the fact that these represent the very small number of Mitsubishi, Daimler and BWM patents in the 1990s, whereas the rest of the industry starts to patent liquid hydrogen containers later on and this results in the increase from 2000 onwards. Gaseous hydrogen and carbon storage are only significant since the turn of the millennium and they never really make a large share of the total number of patents. The very fact that they are patented so late calls for different explanations for each. Gaseous storage of hydrogen is first of all rather conventional and seemingly straightforward. It is perhaps only with the introduction of higher pressure ranges (up to 700 bar) that innovation and thus patenting comes into play. Also, high pressure storage might be a capability of supplier firms rather than of car manufacturers and is therefore left to those to develop. Carbon storage materials are truly a novelty and were studied, in industry and academia, only during a short burst. Some early promising results were never verified and developments were disappointing. For the DOE, for instance, this was a reason to end most of the pure carbon materials research (DOE

2006) and even before that year, the number of patents decreases. A number of patents on this option were nonetheless granted in later years, be it that they often deal with carbon materials doped with metal hydrides. These hybrid materials are also still part of the DOE's portfolio.

The large set of on-board reforming related patents in the dataset (43% of all storage patents) indicates that the industry has seriously explored the possibility of eliminating the need for a dedicated hydrogen infrastructure. Another option for dealing with the expected "chicken and egg" dilemma for hydrogen vehicles and refuelling infrastructure has also been explored. A number of manufacturers hold patents on hydrogen production and refuelling technologies which suggests that they have considered constructing refuelling capacity themselves in order to avoid dependency on other actors such as oil companies. To list a few:

- Mitsubishi has patented a hydrogen filling station as well as a mobile refuelling unit with a hydrocarbon reformer.
- Nissan patented a solar hydrogen production system
- Honda patented a fuelling system, solar hydrogen production system, and a household-size reformer to fuel a car at home.
- GM and Daimler both hold a patent for a photovoltaic hydrogen generator

Entropy in patents and prototypes

Figure 5.3 shows the entropy calculations for the storage technologies present in the patent portfolios as well as in hydrogen vehicle prototypes. For both patents and prototypes the same categories of storage technologies were used. It is clear that findings are not in line with the second hypothesis as formulated in Section 5.3. It was assumed that patents would follow the same convergence dynamics as the prototypes have gone through. However, the entropy in prototypes was initially low and increased later on in a period in which manufacturers explored many options (roughly between 1996 and 2001). After that exploration phase, hydrogen prototype vehicles converged on high pressure hydrogen storage and entropy decreases sharply as a result. In contrast, entropy in the patent portfolios is relatively high throughout the timeframe and has even increased in the last decade.

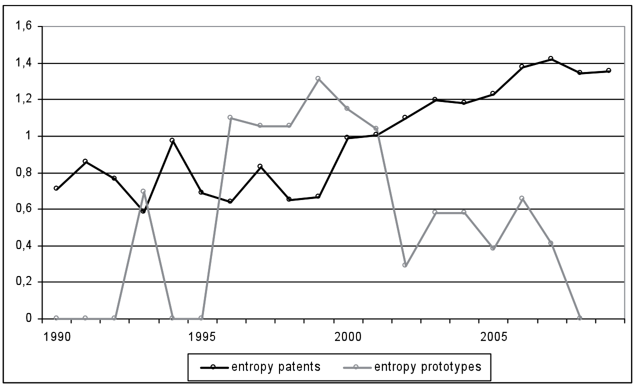

Figure 5.3: Entropy of technological options in patents and hydrogen vehicle prototypes

The hypothesis was based on a somewhat linear model of innovation in which (basic) R&D results in patented technologies. Those technologies are then subsequently tested in prototype vehicles. From that model it would follow that patents converge towards the dominant combination of fuel cells and gaseous storage in the years before this happened in the prototypes. The findings here however imply that such a linear model does not hold here and that prototypes and patents serve somewhat different purposes within firms' technology portfolio management approaches. One possible explanation of these findings could be that prototypes are just as much marketing tools as they are R&D tools. That is, on the one hand prototypes serve, linearly, as test platforms for technological components and configurations and in that respect one would assume that similar technologies can be found in prototypes as well as in patents. On the other hand, the marketing aspect of prototypes entails that prototypes are used to demonstrate technological progress and the firms' ability and desire to move along with zero-emission vehicles. Technologies that are too experimental are not suitable for that purpose as they could jeopardize the functionality of the prototypes. The latter is also of importance to the testing and further development of the fuel cell. As a number of firms have indicated, the emphasis is currently on the development of less expensive and more reliable fuel cells and this is done best with reliable storage systems rather than storage systems that deliver large vehicle ranges.
Car manufacturers thus equip their prototype vehicles with high pressure hydrogen storage, as this is the most practical and reliable option so far. The firms might even go as far to exploit the gaseous hydrogen option in their early fleets of hydrogen vehicles. Nonetheless, it clearly does not meet all aspired levels of performance and firms continue to explore other options. Even though these are visible in the patent portfolios, they do not necessarily show up in prototype models.

5.7 Conclusions and discussion

In addition to existing literature on patents held in the car industry, the first and foremost contribution of this paper is the insight it provides in the patent portfolios of major car manufacturers on hydrogen powered vehicles. The firms have patented both conversion and on-board storage technologies and for both they have maintained diverse portfolios with different technological options. The first hypothesis is therefore confirmed. Almost all firms have focused on fuel cells for hydrogen conversion. The ever increasing entropy in storage patent portfolios reflects an active and ongoing exploration of hydrogen storage technologies. Of greater importance perhaps is the finding that exploration dynamics differ so much between hydrogen patent portfolios and hydrogen prototype vehicles. This finding was contrary to the second hypothesis. The very fact that the industry has not picked any winner yet, according to their patenting behaviour, suggests that firms are not satisfied with any of the options: none meets their levels of aspiration. Following the propositions discussed in Section 5.3, this would imply that commercialization will not take place in the short term. However, the prototypes tell another story, given the discrepancy between the trends in patents and prototypes. For now it could very well be that the industry indeed decides to move forward with hydrogen vehicles equipped with high-pressure gas cylinders[27]. Even though 700 bar hydrogen tanks do not meet all targets, especially in terms of vehicle range and energy efficiency, it does seem to be the most practical solution for now.

For any scholar interested in dynamics and strategies of technology portfolio management, these findings raise the question: what is the value of these indicators? A study of patents might reveal dynamics of technology portfolio management in the R&D stage. But its implications for the possible commercialization of those technologies remain unsure. On the other hand, a study of prototypes alone might only show the tip of the iceberg of all technological options that are explored in the industry. Further research could be aimed at studying the complex relation between patenting and prototype development in more detail.

In relation to hydrogen infrastructure build-up, a group of seven car manufacturers has recently announced the introduction of hydrogen vehicles on the market by 2015[28]. In their letter of understanding, they express their desire to build up the hydrogen infrastructure. Such an infrastructure, especially on the side of gas stations, would then probably be targeted at refuelling 350 and 700 bar gaseous hydrogen tanks. But, for an industry that is still searching for better storage options, it would pose an unwanted lock-in if gas stations were not open to other storage systems. From the perspective of hydrogen refuelling infrastructures the challenge is thus to create an infrastructure which, as much as possible, is open to a wide range on-board storage systems in hydrogen vehicles. Only then would it make sense to further explore alternative storage options.

Acknowledgements

I would like to thank Floortje Alkemade for her valuable comments on earlier versions of this paper.

27 Several statements made by representatives of car manufactures during the DOE Hydrogen & Fuel Cell Technical Advisory Committee meeting on the 4-5 November, 2009.

28 In September 2009, Daimler, Ford, GM, Honda, Hyundai, Renault/Nissan and Toyota released a Letter of Understanding on the development and market introduction of fuel cell vehicles.

6. Credible expectations in US hydrogen funding

6.1 Introduction[29]

The importance of expectations in innovation trajectories and wider sociotechnical transitions is widely recognized. First and foremost it is acknowledged that positive expectations of a technological option's future potential are vital to its further development. It is on the basis of expectations that funding for further work is provided and that actors cooperate and coordinate their efforts towards a shared goal (Borup et al 2006). It is no surprise that in the literature on sociotechnical transitions, much emphasis is put on the creation of shared, and hence, guiding vision (Smith et al 2005, Shove and Walker 2007). However, in most cases of (prospective) sociotechnical transitions, there are many competing technologies and trajectories (Geels 2010) and perhaps even more competing visions and expectations surrounding the innovation trajectories. And because resources are finite, only a limited of number of paths can be supported and choices need to be made. These choices, we argue, can not and are not based on actual price and performance characteristics alone. That is, emerging technologies are not 'judged' on what they *can* do, but rather on what they *will be able* to do in the future. Choices between competing transition paths, and between competing technologies within the paths, are thus based on expectations rather than facts (van Lente and Bakker 2010). And, in this paper we ask the question: what makes one option more promising than the other and how is the credibility of such expectations assessed by decision makers? We do so with the aim of deepening our understanding of the fundamentals of technological expectations and their role in the competition between emerging technologies and sociotechnical systems.

We start our analysis from the so-called *sociology of expectations* literature. In this body of literature, most attention is paid to the role of collective expectations. Collective expectations are those expectations that are held by many actors, or at least those that are known and referred to by many.

29 This chapter is to be submitted for publication and is co-authored with Harro van Lente and Marius Meeus.

As these expectations are so widely shared or heard of and referred to, they fulfil a structuring role in innovation processes. Whether actors like it or not, they have to deal with these expectations in some way or another. It might be that an actor draws legitimation from these expectations for his or her own work, but it can also be that an actor can not ignore the forceful expectations and needs to join in on the development activities. In other words, actors can be both enabled and constrained by expectations in their innovation activities.

To answer our question, such a conceptualization of technological expectations, with an emphasis on the collectivity and the structuring role of expectations, is not sufficient: the role of agency is obscured and, more precisely, it is unclear how collective expectations come about and why these are thought to be credible. In this paper we address two of these issues. First, we address the complex relation between those actors that try to shape positive expectations of 'their' technologies and those actors that, as a result of their role in the innovation process, need to assess those expectations and base their technology selection on those assessments. Second, we study the actual assessment of expectations in that same process and the notion of credible expectations vis-à-vis incredible expectations. We do so in a case study on the US Department of Energy (DOE) Hydrogen Program. The Hydrogen Program fulfils a double role as it acts as a proponent of the hydrogen car and wider hydrogen energy systems, which compete with other future energy and mobility options such as the electric car. And at the same time, it acts as a selector of specific promising and desirable enabling hydrogen technologies that compete among one another. In both processes, expectations of technological progress and future market potential are critical. And for expectations to be powerful, they need to be assessed as credible. To be clear, it is not our intention to distinguish between credible and incredible expectations ourselves, but rather to study how both technology enactors as well as technology selectors make their assessments of the credibility of expectations. The literature on technological expectations rightfully claims it does not attempt to look *into* the future, but rather to look *at* the future. We propose to look a little bit closer.

6.2 Credible expectations

Two theoretical concepts are at the heart of this paper and the analysis that is presented: the quasi-evolutionary model of innovation and the sociology of expectations. The starting point for evolutionary models of innovation is that different technological variations are developed and compete for survival in the selection environment: the market (Dosi and Nelson 1994, Nelson and Winter 1977). The quasi-evolutionary model (van den Belt and Rip 1987, Schot 1992, Rip et al. 1995) stresses the connection between variation and selection through anticipation and strategies of various actors. Actors anticipate the selection environment because they have some understanding of its future demands, for instance by extrapolating ongoing improvements. Actors will also seek to modify selection environments, by voicing expectations or with other moves like forging strategic alliances.

The sociology of expectations has taken the notion of technological expectations a step further and the basic claim in this body of literature is that positive technological expectations are vital to

innovation processes, in terms of stimulating, steering and coordination of the development by the actors involved.
Together, the notions of variation and selection and the vital role of expectations give rise to a conceptual model for the competition between emerging technological options: *arenas of expectations* (Bakker et al 2011). The arenas of expectations are the battlegrounds on which the different actor communities, the so-called enactors, that all advocate their own technological variation, fight their battles (Figure 6.1). Winners of these battles are those communities whose option is positively selected by the technology selectors and as a consequence receive a mandate to continue the development of their variation.

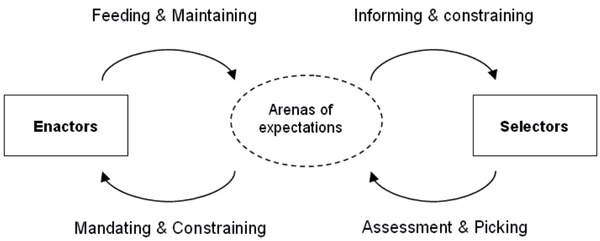

Figure 6.1: Arenas of expectations as linchpin between the enaction and selection of emerging technologies (Bakker et al 2011).

In the case of emerging technological systems, investment decisions (and other pre-selections) have to be taken, by the so-called selectors, in an early stage of development, when the technological systems are not in place, yet. In this situation uncertainty is much higher and actors have to make decisions based on expectations rather than facts. They need to find some ground for rational decisions while they are surrounded with uncertainty (Rappert 1999). Through this model, the role of agency in the competition between emerging technologies is made more explicit in comparison to the sociology of expectations literature. The actor groups on both sides, the enactors and selectors, are assumed to make assessments of the credibility of the diverse technological expectations that are circulated. Enactors need to communicate expectations that will be assessed as credible by their enactors, and they simultaneously question the credibility of their competitors' options (Bakker et al 2011). Selectors, in turn, invest in, or otherwise support, one or more options that are most credible according to their assessments.

In the case of hydrogen technologies, numerous technological capabilities and societal aspects are indeed very uncertain. In some niche markets commercial applications are used already, but the first commercially viable hydrogen car has yet to be built. And at this stage, a lot is known about the laboratory performance and specifications of the options, but far less has been learned about real-life use, system integration, possible learning curves, and economies of scale. Expectations of possible improvements in the future are thus very much part of decision making process, for enactors and selectors alike.

Technology selection

In the expectations literature so far, not much attention has been paid to the actual assessment of expectations and their role in the selection of promising technologies. Again: *what makes one expectation more credible than another?* It is recognized that expectations can stimulate, guide and coordinate innovation efforts when they are shared among relevant actors or at least form part of the collective repertoire of future-oriented stories (Borup et al 2006, Konrad 2006). Often, a macro-perspective is adopted to study the influence of such collective expectations. However, a more detailed micro-analysis might shed light on the actual assessment of expectations and the link between expectations and technology selection. Recently, this has been done in relation to hypes: how do actors respond to, and make use of, the dynamics of hype and disappointment? (Konrad et al. 2009, Wüstenhagen et al. 2009)

It is shown how actors respond rather strategically to both the hype phase (which attracts actors) and disappointment phase (in which actors 'step out'). Still, this work does not address the assessments that individual actors make in relation to the concrete expectations of technological options. For instance, a venture capitalist might respond to hype by acquiring a share in a business because the very hype is enough to generate profit on that share (Wüstenhagen et al. 2009), but the venture capitalist does not necessarily share the high expectations that circulate during the hype and is perhaps not even interested in the success of eventual market introduction of hydrogen technologies. Other actors that are more interested in the final outcome, such as successful commercialization of a product or the fulfilment of societal goals, do need an understanding of the fundamentals (cf. fundamentals of a financial stock) of the expectations and be convinced of the 'realistic' chances that technology has of becoming successful.

Do other strands of literature provide insight in the technology selection process and the role of expectations therein? Literature dealing with these types of questions, most often in industry settings, refers to terms such as 'technology strategy', 'portfolio management' (Cooper et al 2001) or 'technological foresight' when a longer time span is taken into account (Lichtenthaler 2004, Reger 2001).

Different strategies are used to assess and manage R&D processes. Often, performance goals are set and progress is assessed in relation to these goals. R&D investment then becomes an iterative, milestone-oriented process in order to reduce risk and maintain the flexibility of a portfolio of options (Bowman and Hurry 1993, Eisenhardt and Tabrizi 1995, McGrath 1997) and the investment decisions might take the shape of a formalized management style such as stage-gating.

Whereas the technology strategy literature is most concerned with selection processes in firms, our case study is situated in the realm of public funding: governments engage in foresight activities and may or may not choose to select a number of technological options. Governments do take a different approach to technology selection and they often rely on experts' assessments of the technological potential and the future society in which they are supposed to make a difference. Even though the processes are somewhat different, the literature on governmental use of technological foresight focuses on the process aspects as well; what people are involved, how are foresight activities managed, and what is its impact on policy making etc. (Shehabuddeen et al 2006, Propp and Rip 2006).

6.3 Enaction and selection in a technological hierarchy

In this paper we propose to move beyond the generic frameworks for technology selection and take a closer look at the actual assessment of an emerging technology's future potential. To do so we make use of our conceptual model of arenas of expectations. The distinction between enactors and selectors is essential in the analysis, but it is certainly not straightforward and it is very much dependent of the context and timing of the enaction and selection process. In the following section we elaborate on the relation between enactors and selectors after which we move on to our case study of the DOE Hydrogen Program.

The question of technology selection relates to the assessments made by those actors that decide whether or not to pursue or support the development of technological options. These actors have some need for a (technological) solution to a problem that they face or expect to face in the future. Or, they merely see future economic opportunities that might be realized with the promising technology. In any case, those actors cannot support all available options and need to select only one or a limited number of options as they are bound by resources. In the selection process they are confronted with a number of options that are developed and advocated by technological communities of enactors. In this framing, the distinction between the enactors and selectors might be straightforward, but in practice it is not.

We argue that the roles of enactor and selector are much more dynamic and not easily separable. These roles are dynamic in the sense that any actor can perform both roles sequentially or even simultaneously. First, an actor might select a technological option and enact from that moment onwards. For instance, a car manufacturer that in its role of selector decides to engage in the development of fuel cell technology becomes an enactor afterwards when tries to find support from governments and acceptance by future customers. The same goes for a scientist that enters a research field, say metal hydrides for hydrogen storage, and thereby effectively selects that field and becomes an enactor of the same field from there onwards.

Second, an actor that is active in the field of hydrogen is an enactor of the hydrogen option as a whole, but he or she remains a selector for component options such as for hydrogen storage. In Figure 6.2 a technological hierarchy of hydrogen technologies is sketched in which one could position such an actor as an enactor-of-the-system and selector-of-components. In this hierarchy the emphasis is on storage options, but there are multiple options for production, distribution and conversion as well. To illustrate, a lead developer of hydrogen cars in an automotive firm enacts the hydrogen vehicle as a whole (and probably of the hydrogen vision as well) and at the same time acts as a selector for the most promising storage method to be incorporated in the vehicle.

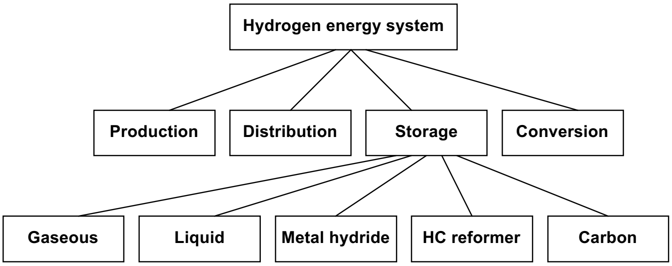

Figure 6.2: A technological hierarchy of hydrogen technologies, the DOE Hydrogen Program can be situated between the hydrogen energy system, which it enacts, and the enabling component options which its selects.

In our case study we will show how the actors that are involved in the DOE Hydrogen Program perform both roles and how, as a consequence, enaction and selection are very much interrelated.

6.4 The DOE Hydrogen Program case study

In 1977 the Department of Energy (DOE) was created by the US federal government and it is historically one of the major federal sponsors of energy related R&D (Irvine and Martin 1984). From its start, the department has been one of the central actors in federal initiatives on alternative vehicle propulsion technologies development and its decisions influence decision making worldwide (Schaeffer 1998). And, from 1990 onwards hydrogen and fuel cells were given top priority as a result of the `Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act'. The act called upon the secretary of energy, James D. Watkins, to develop a 5-year '*program management plan that will identify and resolve critical technical issues necessary for the realization of a domestic capability to produce, distribute, and use hydrogen economically within the shortest time practicable*'. The act was followed by the *Energy Policy Act of 1992*, the *Hydrogen Future Act of 1996*, and the *Energy Policy Act of 2001* which all either focused, on or at least included, hydrogen technology development. In the middle of the hydrogen hype, the FreedomCAR and Fuel Partnership were founded from the cooperation between DOE and USCAR (the US Council for Automotive Research, consisting of Ford, GM, and Chrysler). These bodies were aimed to spur the development of hydrogen vehicles by the US car makers.

President Bush's Hydrogen Fuel Initiative directed '*$1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles*' (Bush 2003). Together with the 2005 Energy Policy Act, which confirmed the need for hydrogen technology development, the HFI has resulted in the DOE's Hydrogen Program. Annual funds for hydrogen development have increased from $150 M in 2004 to $ 276 M in 2008, since 2009 the budget has decreased slightly (see Figure 6.3).

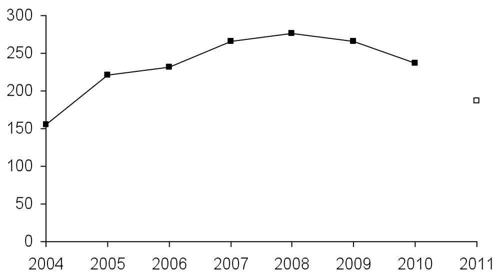

Figure 6.3: The FY 2011 request totals $137 M, there is a shift from a wide array of hydrogen technologies to a focus on FC's. The 2011 figure represents the funding request[30].

The latest decrease in hydrogen funding is in part due to lower expectations of hydrogen in general: the disappointment that followed the period of hype. However, another and more detailed view reveals that hydrogen was very much an idea of the Bush administration and the new administration had no such commitment to hydrogen. In an interview, the newly appointment Secretary of Energy Dr. Steven Chu referred to hydrogen as an faraway option that needs four miracles to work and therefore sees no future for hydrogen (Bullis 2009). The four miracles are needed on hydrogen production, hydrogen infrastructures, hydrogen fuel cells, and hydrogen storage.

Furthermore, the credit crunch and the subsequent recovery act have directed the federal government to focus on more short term options that can stimulate the economy more directly than a long-term option such as hydrogen could ever do. To illustrate, the DOE was granted a 75% increase in budget as part of the 2009 Recovery Act, an additional $38.3 billion (Alvarez 2009), but less than $50 million was allocated to hydrogen and fuel cells.

The disappointment, the association with the former administration and the secretary's disbelief have put hydrogen funding in the US under pressure. All of this culminated when Dr. Chu proposed to end all hydrogen funding in the 2010 budget. It was only because the US Congress, after intensive lobbying by the hydrogen community, voted to restore the hydrogen budget that the hydrogen program was able to continue with roughly the same levels of funding. To the hydrogen community however, it was unsure to what extent the funding would be upheld in the following years.

Even though the DOE is the most prominent of hydrogen R&D funding departments in the US (Solomon and Banerjee 2006), it is certainly not the only one. The Department of Transportation for instance has been heavily involved in hydrogen and fuel cells development as well, for instance through hydrogen (fuel cell) bus projects. Also, the Department of Defence has had a long history of interest in hydrogen technologies. In theory, hydrogen could be the energy carrier that makes the US army independent of logistically problematic oil supplies and rely on locally produced hydrogen (with on-site solar and wind power). But despite the other department's involvement, the DOE hydrogen

30 EERE R&D Program Update, February 23 2010, HTAC meeting presentation by Rick Farmer, Acting Program Manager of the Hydrogen Program.

budget does account for roughly 60% of total US federal hydrogen funding (Rose et al. 2008) and we limit our analysis to the DOE Hydrogen Program.

The development of the DOE hydrogen budget is clearly influenced by dynamics of hype and disappointment and by politics at the national level. In our case study we take a closer look at the process underlying the development of the budget and the technological options that are supported within the budget. This is a story of enaction and selection of the hydrogen vision and its enabling technologies. The case study is divided in a section that is dedicated to the enaction of the hydrogen vision: how to put to the fore a credible vision? The enaction of the hydrogen vision is studied from the perspective of the Hydrogen Programs advisory committee HTAC (Hydrogen and Fuel Cell Technical Advisory Committee). The second section of the case study is most concerned with the selection of enabling technologies within the DOE Hydrogen Program. The research was conducted through an analysis of DOE documents, minutes of the HTAC meetings (see Table 6.1) and attendance of the November 2009 meeting. In the context of the DOE's technology selection procedures, short interviews were held with DOE staff members.
In Sections 6.5, 6.6, and 6.7 we describe the enaction and selection processes that have taken place with regard to DOE's Hydrogen Program. In Section 6.8 we analyze what 'credible expectations' exactly are in the context of the hydrogen program, how the involved actors have dealt with these expectations, and how enaction and selection are very much interrelated processes.

Table 6.1: Meetings of the HTAC included in the analysis

#	Date
1	October 2-3 2006
2	November 17 2006
3	January 9-10 2007
4	May 16-17 2007
5	July 31-August 1 2007
6	December 18-19 2007
7	May 13-14 2008
8	July 22-23 2008
9	November 6-7 2008
10	February 18-19 2009
11	July 15 2009
12	November 4-5 2009
13	February 23 2010[31]

31 At the time of writing this paper, the minutes for the latest meeting were not available yet, only the meeting's agenda and speakers' presentation slides were used in the analysis presented here.

6.5 The HTAC as hydrogen enactor

The current Department of Energy's Hydrogen Program was started in 2004 and it has acted as a major hydrogen technologies selector in that capacity. However, in terms of the hydrogen vision, the program acts rather as an enactor. That is, the hydrogen program staff members had to convince their Secretaries of the viability of hydrogen as such. This distinction highlights the double roles that actors can have in the enaction-selection game. In this section we first discuss the role of the hydrogen program as an enactor of the hydrogen vision. To do so, we have studied the minutes of the Hydrogen Technical Advisory Committee (HTAC) meetings that have taken place since October 2006. The HTAC is essentially an advising body to the Secretary of Energy and US Congress, installed through the EP ACT of 2005. Its task is to advise the Secretary on all aspects of the hydrogen program, including specific hydrogen technologies, activities, and issues with regard to the environment, safety and economy. In practice, the HTAC is also a strong advocate[32] of the hydrogen vision and this specific role has increased with the appointment of the new secretary and increasing doubts that have surrounded the hydrogen vision. For our purposes, the HTAC meetings serve as a testament of hydrogen enactors' deliberations and actions towards constructing and putting forward a credible hydrogen vision. The HTAC is not the only enactor of hydrogen technologies towards US policy makers, amongst others the National Hydrogen Association and the US Fuel Cell Council also play an important role, but the HTAC serves as an example of the types of deliberations that enactors may have in their struggle to enact their option. As we will show, the HTAC also provides advice on selection-related matters in relation to DOE's technology portfolio as outlined in the technological hierarchy of hydrogen technologies. And some of our findings from HTAC will be used in the technology selection section as well.

The HTAC consists of representatives from science, the car and energy industry, venture capital, and dedicated hydrogen technology firms[33]. DOE Hydrogen Program staff is present during the meetings and provides HTAC with updates on the budget, technological and scientific achievements etc. Furthermore, the HTAC invites speakers to brief the committee on developments in industry, other US Departments and the international situation regarding hydrogen.

The remainder of this section presents the analysis of the HTAC meetings and the analysis is divided in three chronological phases in which the focus shifts from rather unproblematic and general

32 HTAC's role as hydrogen advocate is reflected in its mission statement which was adopted by committee's members during the July 2008 meeting: *"Our vision of the future is that hydrogen will become a universal and economically competitive energy carrier, progressively substituting for carbon-based fuels over time, to meet the needs of the planet. Hydrogen will be produced from a number of sources, increasingly with the lowest possible carbon impact. To realize this vision, the nation must aggressively introduce to the market the hydrogen-based technologies that are available now and those that will be developed in the future. HTAC's role is to aid the nation in developing a policy framework that takes into account the technical, political, social, cultural, environmental and commercial requirements of the transition to hydrogen"*.

33 For a list of current and past members of HTAC and its meetings, see: www.hydrogen.energy.gov/advisory_htac.html

discussions on hydrogen development and deployment, to ultimately the question of how to influence US policy makers to restore and maintain hydrogen funding levels.

First phase: moving forward

The first HTAC meetings were held in 2006 during the later years of the Bush administration. Hydrogen funding was relatively stable and the discussion in the committee dealt mostly with the question: how to move hydrogen forward? Central to this was the Hydrogen Posture Plan which was released in December 2006. This plan dealt with all elements in the hydrogen system, such as fuel cells and storage technology development, but also with commercialization, deployment and the build-up of a hydrogen infrastructure. Essentially, it presented hydrogen as a long-term option which would only enter markets in 2015. For the HTAC members this timeline was not satisfactory in the sense that it did not match with the needs of society in terms of climate change and US competitiveness. Furthermore, they believed that the industry, most notably the car industry, was more advanced in terms of technology readiness than it openly stated and that the committee should have urged for more short-term action to achieve earlier market deployment. Government policy should therefore not have aimed at R&D only in this stage, also been engaged with infrastructure build-up, the setting of technical standards and safety codes, education of both the industry workforce, and civil servants that will have to deal with hydrogen station permits.

In order to achieve these goals, HTAC recommended DOE Secretary Samuel Bodman to set up an Interagency Task Force (ITF) to coordinate and streamline the diverse initiatives in the different federal agencies and departments, such as the departments of Transport and Defense and the Environmental Protection Agency. One of HTAC members even went so far as to suggest the possibility of a '*Hydrogen Czar*[34]' as 'ultimate-decision maker at the federal level. The rest of the committee did not support this suggestion however. Following the recommendations, the ITF was indeed set up and the aim was to bring together high-level representatives of the different organizations[35].

By the end of 2006, mid-term elections gave Democrats a bigger say in Congress and this was generally seen as favourable to hydrogen by HTAC members. The Democrats had campaigned on alternative fuels and there was no reason to assume that hydrogen would not be part of the portfolio.

Second phase: reframing hydrogen

Whereas in the first phase some concerns were voiced about diminishing attention for hydrogen technologies, from the May 2007 meeting onwards these concerns were ever more present in the discussions. One indicator of diminishing attention was the apparent difficulty in attracting high-level

34 The concept of a Czar refers to the 'Oil Czar' in WOII, Harold Ickes, who was responsible for the coordination of oil production and distribution for the war effort (Yergin 1991).

35 The following agencies participate in the ITF: the departments of Agriculture, Commerce, Defense, Energy (DOE), Homeland Security, Transportation, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the United States Postal Service, the Executive Office of the President, the Office of Management and Budget, and the White House Office of Science and Technology Policy (OSTP)

representatives from the different agencies to take part in the Interagency Task Force. Even from DOE itself the level of commitment was not satisfactory to HTAC. Furthermore, the rise of plug-in electric vehicles and pure battery-electric vehicles was perceived as a threat to hydrogen developments as both were feared to '*chip away*' funding from hydrogen (meeting #4 p3). The same goes for private funding, from venture capitalists, which was harder to acquire for hydrogen technologies than for instance for battery developers. Within the HTAC it was recognized that hydrogen suffers not only from stronger competition from other options, but also from over-promising by hydrogen advocates in the past.

To counteract these negative dynamics, the members argued that the hydrogen community should not bring to the fore even greater promises, but rather '*hard facts*' and practical achievements. And in terms of the competition, it was thought that hydrogen should not try to compete with the other options, but rather be positioned as one of the viable options. If successful, such an approach could '*enlarge the pie*' as a whole instead of just trying to get a '*bigger slice*' of the existing one.

Still, hydrogen has always been perceived as a long-term option and some in HTAC feared that greater awareness of global issues such as the climate and diminishing oil supplies would increase the focus on short-term options. Therefore it is not enough to enlarge the pie, but it should also be stressed that hydrogen has a short-term potential as well. During the July/August meeting of 2007 this need was also stressed by Assistant Secretary Andy Karsner. He explained that Secretary Bodman had moved beyond the question of whether the US should act on the climate issue, and now asked the question of how to act. Secretary Bodman thus felt the need for hydrogen to show how it could precisely fit in such a climate agenda. The hydrogen community, including HTAC, was expected to respond with '*nuts and bolts*' ideas that '*move the needle in a measurable way*'. From a political perspective time was running out as well. The secretary had only 18 months to go before the new administration would take over and he was in need of practical and visible results of the hydrogen program.

The HTAC therefore decided to stress the potential of hydrogen in early niche markets in which hydrogen technologies can make a difference on the short term. Government could and should play an active role through procurement of hydrogen and fuel cell products such as forklifts and emergency power supply units. Furthermore, it should be stressed that hydrogen technologies were 'ready' and that for instance hydrogen production from natural gas was already commercially viable: the $3 gallon of gasoline equivalent price for hydrogen was acceptable (7 p5). On that basis, funding could be taken away from other long-term production pathways and shifted towards short-term critical needs such as fuel cells and storage. Later in the same meeting, this argument was also used to position high pressure gaseous storage as acceptable: a $2000 gas tank could provide a 300-400 mile range which would be sufficient for early hydrogen vehicles (7 p19). There was thus no reason to wait with the build-up of a national hydrogen refuelling infrastructure.

As part of the reframing of hydrogen from a long-term option towards hydrogen as short term option it was even proposed to use the slogan: '*hydrogen is change you can believe in*' as one of the possible talking points for the candidates for the presidency. And, the most important argument should have been that the US was not only the only country that pursued the development of hydrogen technologies and other countries were moving forward at a faster pace. Especially the EU and Japan were said to be the main competitors and the US should not run the risk of falling behind and missing out on the economic opportunities that hydrogen presented.

Third phase: educating the new Secretary

From the moment President Obama was elected in November 2008, the HTAC discussions dealt mostly with the possible ways to convince the new administration of the societal and economic potential of hydrogen technologies and the need to compete with the other nations. The chairman of HTAC had held a meeting with newly installed Secretary Dr. Steven Chu in February 2009. The Secretary was positive about stationary fuel cells and some mobile applications such as forklifts and buses. Other applications were more problematic in his view, because of the necessary scale of hydrogen production and the required refuelling infrastructure (10 p2). The chairman's general feeling after the meeting was that the Secretary had '*sophisticated skepticism*' and could possibly be swayed by '*technically meritorious arguments*'.

Already, HTAC members felt that the US was more and more in danger of falling behind the other countries and the Secretary's skepticism was yet another signal that hydrogen was under pressure. Also, as a result of the economic crisis, energy prices had dropped and this lessened the perceived need for alternative fuels. Even more than in the previous phase, the committee members stressed the need to get hydrogen back onto the agenda. Therefore, they proposed to connect hydrogen to a range of issues in order to underline hydrogen's versatility. They felt it was necessary to relate hydrogen to the increase in renewable electricity production: hydrogen could very well be a buffering energy storage solution. Furthermore, it was suggested to relate the hydrogen vision the nuclear power debate once again.

The perceived weaknesses of hydrogen technologies should be countered as well. For instance by stressing that hydrogen vehicles could very well compete with PHEV's in terms of price and performance. Future regulations were thought to push the conventional car out of the market and hydrogen should thus no longer be compared with the old technology but rather with its future competitors. The investment cost that the Secretary was worried about should be compared with the costs, $370 billion, of oil imports. Taken together, with these arguments the Secretary might be persuaded to be more of a 'believer'.

Nonetheless, in May of 2009 Secretary Chu announced DOE's fiscal year 2010 budget in which hydrogen was zeroed[36]. Except for $68 million for dedicated fuel cells R&D, hydrogen was out of the budget. As Deputy Assistant Secretary for Renewable Energy Jacques Beaudry-Losique explained during the November 2009 meeting, Secretary Chu had taken the HTAC advice serious, but the decision not to push through with hydrogen had a lot to do with a balance between short, mid, and long term options. And for hydrogen to be successful it probably needed at least 'half a miracle', in Beaudry-Losique's wording, and with all things considered hydrogen was still a long term option that might be realized in the 2020-2050 timeframe at its earliest. Hydrogen and fuel cells have suffered from

36 www.nytimes.com/2009/05/08/science/earth/08energy.html

lack of understanding and overpromising but at the department there was not so much disbelieve but rather a wide scope of options and priority was then with the short and mid term options, according to Beaudry-Losique.

It is only because of Congress that hydrogen funding was nearly fully restored in the final budget. The initiative in Congress to restore the hydrogen budget was the result of a campaign from organizations such as the National Hydrogen Association, the Californian Fuel Cell Partnership, and the US Fuel Cell Council. However, for the members of HTAC this one time achievement, aimed at the continuation of on-going projects, was no guarantee that the future of hydrogen was indeed safeguarded. For one of HTAC's car industry representatives, the Secretary's disbelief in hydrogen was reason to end his membership of the committee.

Once again the HTAC discusses the message that needed to get through to the DOE's leadership to educate them on hydrogen related matters. Even more emphasis should be put on current achievements and niche-market success and the role of hydrogen in the short term. But it proved to be difficult to be heard by the Secretary. The HTAC only succeeded in setting up a half hour meeting with the Under Secretary Kristina Johnson. In contrast, hydrogen's competitors did have access to the Secretary and the new administration. For instance, it was mentioned that Joseph Romm, a well-known critic of the hydrogen vision, was influential in the new administration through his membership of the Center for American Progress. Different routes were discussed to get the hydrogen message across. Some suggestions were: writing op-eds, grass roots initiatives to show early market success, and to appeal to the Secretary as a scientist with scientific facts. For instance it was also discussed whether a direct letter should be sent to the Secretary, which he might not read at all, or have the Under Secretary deliver the letter to guarantee that Chu actually receives it in person. Furthermore, should the letter be short and concise or rather detailed to appeal to him as scientist?

One of HTAC's most striking responses was to question whether storage should still be high on the hydrogen research agenda. Since most manufacturers seemed to move forward with high-pressure storage, the storage problem might no longer exist. The DOE targets were already revised and gaseous storage was now deemed viable, but costs still had to go down and materials research was therefore desirable, also because it might make possible storage at lower pressures which would benefit safety and energy efficiency. Effectively, HTAC wished to clear the list of problems, or miracles in Secretary Chu's wording, so as to be able to present hydrogen as a viable short term option, rather than one that needs a lot of R&D. The enaction of hydrogen was thus directly effected the selection of underlying hydrogen technologies. This was also visible in the 2011 budget request, in which storage got less attention and even more of the funding was shifted to work on fuel cells[37].

37 www.hydrogen.energy.gov/pdfs/htac_feb_23_10_program.pdf
(presentation by Hydrogen Program leader Rick Farmer during meeting #13)

6.6 Selecting hydrogen technologies

Whereas the enaction of hydrogen technologies is a process that is chaotic and hardly transparent, the selection of technologies within the DOE Hydrogen Program is very much rationalized and structured. Naturally, the process of selection is something that a selecting actor or organization can control whereas the enactors are much more dependent on the goodwill of the selectors. The DOE has organized the selection process as one of stage-gating in which the options move stepwise from basic research towards selection for commercialization. This implies that the different options must show progress in order to stay in the technology portfolio.

As part of this stepwise approach, R&D targets play a central role in the selection of viable hydrogen technologies. In the Hydrogen Program, these targets are set for fuel cells, storage systems and hydrogen production technologies. Here we focus on the selection of viable storage options and therefore those targets are of most importance to our case study. An overview of the DOE storage targets is provided in Table 6.2 (DOE and FreedomCAR & Fuel Partnership 2009). Initially these targets were set in 2003 within the FreedomCAR and Fuel Partnership. Basically, the targets were based on the performance of conventional gasoline cars and the intent was to provide hydrogen cars with the same drive range and passenger comfort. In practice this meant that hydrogen cars would need to carry enough hydrogen for a 500 km range without compromising space, performance, safety and costs. Therefore, the targets address the weight (gravimetric density of hydrogen in the storage system), the volume (volumetric density), energy efficiency, safety aspects (permeation and leakage) and the costs of hydrogen storage systems. The resulting targets are supposed to be met subsequently in 2007, 2010, and 2015. As developments progressed, both in basic science and industry, it became clear that the targets could be lowered and they were adjusted in 2009[38]. The targets were lowered because fuel cell cars proved to be more efficient than earlier estimates (in part due to hybridization) and the expectation that cars in general will become smaller because of customer demand and governmental regulation. Consequently, less hydrogen needs to be carried on board. Furthermore, with the dedicated vehicle architectures, it is possible to incorporate larger storage systems without compromising usable space.

38 It is most likely that the targets were lowered because they were set too high for any of the options to reach them; lowering targets is thus also a way to deal with disappointing R&D results.

Table 6.2: An overview of the most prominent DOE storage targets. These were initially set in 2003 (old) and revised in 2009 (new). Storage system cost targets are not determined yet.

Target	2010 (new)	2010 (old)	2015 (new)	2015 (old)	Ultimate Full Fleet
System Gravimetric Density (% wt)	4.5 (1.5 kWh/kg)	6 (2.0 kWh/kg)	5.5 (1.8 kWh/kg)	9 (3 kWh/kg)	7.5 (2.5 kWh/kg)
System Volumetric Density (g/L)	28 (0.9 kWh/L)	45 (1.5 kWh/L)	40 (1.3 kWh/L)	81 (2.7 kWh/L)	70 (2.3 kWh/L)
System Fill Time for 5-kg fill (Fuelling Rate, kg/min)	4.2 min (1.2 kg/min)	3 min (1.67 kg/min)	3.3 min (1.5 kg/min)	2.5 min (2.0 kg/min)	2.5 min (2.0 kg/min)
Storage System Cost ($/kg H2)	TBD	133 ($4/kWh)	TBD	67 ($2/kWh)	TBD

With each storage option come different problems and different problematic targets and there are always trade-offs between the different criteria. For instance, for high-pressure storage the volumetric density is of greatest concern: can high-enough pressures be realized so as to minimize volume? With 700 bar systems, the revised 2010 volumetric targets are almost met, but concerns remain with regard to the energy efficiency and safety of those systems (Figure 6.4). For metal hydrides it is mostly the gravimetric density that remains problematic (due to the weight of the metal alloys) and for those alloys that are promising in terms of weight it is often the temperature of operation that are problematic.

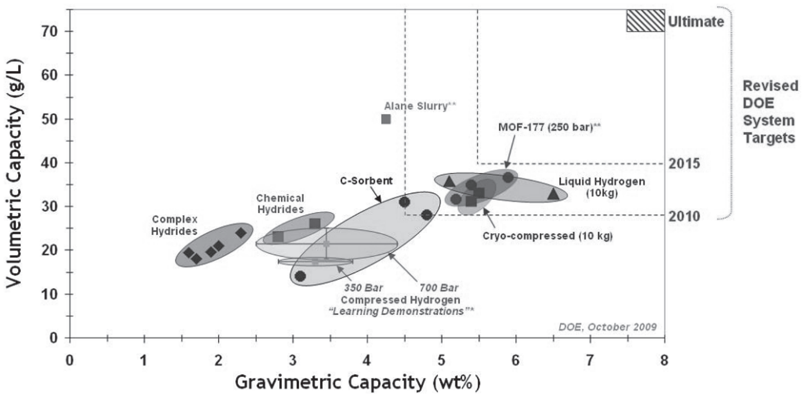

Figure 6.4: The main storage options and their distance to the DOE storage targets for volumetric and gravimetric capacity. These are not the only criteria and the options that meet these two criteria fail on others such as temperature of operation and energy efficiency. (source: presentation slides from the Hydrogen Program manager during the November 2009 HTAC meeting)

Expectations assessment

All storage technologies that are supported within the DOE Hydrogen Program are assessed as to whether those options are capable of meeting the R&D targets. This assessment is done on a yearly basis during so-called 'Merit Review and Peer Evaluation' meetings. All running R&D projects are reviewed and their progress is evaluated. In case the results and progress for a technological option

are questionable, a specific process is set in motion to determine whether or not the option should continue to be supported: a go/no-go decision.
Proponents of such technologies need to convince their selectors, the DOE and the experts it consults, of the credibility of their option: they need to tell credible expectations. In the following, we describe two no-go decisions that were made. The first is about on-board fuel processing and the second is about undoped single walled carbon nanotubes[39]. These decisions and the underlying processes provide insight in the actual expectation assessment as it is performed by the DOE as technology selector[40].

On-board fuel processing

R&D on on-board reforming of gasoline, ethanol, methanol and natural gas was funded by DOE for over a decade. In short, this option allows hydrogen fuel cell vehicles to carry liquid hydrocarbon fuels that are reformed to hydrogen on-board the vehicle. By doing so, the need for a hydrogen storage system is eliminated and no dedicated hydrogen refuelling infrastructure is needed. The liquid fuels are easier to transport and distribute and this would demand lower capital investments than a hydrogen infrastructure. In theory, on-board reforming and use of the hydrogen in fuel cells would result in lower emissions as compared to using the fuels in combustion engines directly. Next to that, it would allow the development and commercialization of hydrogen fuel cell vehicles without the immediate need for infrastructure build-up. Thus being only a small improvement over today's conventional cars, it was always seen a transitional pathway to zero-emission hydrogen vehicles.
However, over the years concerns have grown over the desirability of such technologies from both an environmental as well as a performance perspective. These concerns have led to a formal go/no-go decision to be made in June 2004 (DOE 2004). An expert panel was set up to provide a recommendation on technical performance and progress. On the basis of their input, DOE's go/no-go decision team came to recommend the termination of on-board fuel processing development.
The arguments that were used are as follows. Even though progress has been made in terms of working prototypes and proofs of principle, the targets for start-up times and start-up energy were not met. And also, there was no reason to assume that these targets could be met in the future. In other words, a pathway to increase the performance was not identified.
Perhaps even more important was the fact that similar emissions reductions (as compared to gasoline cars) could also be achieved with gasoline hybrid vehicles: there was no longer need for such complex solutions. And the car industry, involved in the hydrogen program though the FreedomCAR partnership, had also indicated that it no longer took interest in on-board fuel processing.

39 Documents on the go/no-go decisions are available on the Hydrogen Program website: www1.eere.energy.gov/hydrogenandfuelcells/plans_implementation_results.html

40 Similar decisions were made for sodium borohydrides and several specific materials within the metal and chemical hydrides programs.

Undoped single walled carbon nanotubes

Carbon nanotubes were believed to have enormous potential for hydrogen storage after researchers claimed they could store up to 50 wt% of hydrogen (Dagani 2002). Although the most promising results were always questioned and were not reproduced in following studies, the DOE decided to support this option from 1992 onwards.
Basically, hydrogen storage in carbon materials is possible because hydrogen molecules can occupy the interior space of the tubes and as such adsorb to the carbon surface. And, it was thought, with the enormous surface of the tubes interiors enough hydrogen could be stored so as to make it practical for vehicular storage application.
However with progressing research, it was soon found that the pure and undoped nanotubes could not achieve spectacular weight percentages of adsorbed hydrogen. Nanotubes that were doped in other hydrogen storage materials, such as metal alloys, did prove some potential though. It is even believed that some of the early promising findings were the result of metal contaminations in the supposedly clean nanotubes. In 2006 a go/no-go decision process was started to determine whether or not to continue the research on carbon nanotubes (DOE 2006). The main criterion that was formulated for the required performance, as derivate from the DOE storage targets, was that the materials should be able to reach 6 wt% of hydrogen storage capacity on a materials basis at room temperature. In practice, only 0.6 wt% was achieved at room temperatures and 3 wt% at cryogenic temperatures (77K). Furthermore, from the review it was shown that no pathway could be identified towards increasing the percentages without adding other materials to the carbon nanotubes. As a result, a no-go decision was made on further funding of research on pure undoped nanotubes. A go decision was made with regard to doped nanotubes. These have proven their potential to store large amounts of hydrogen, both at room temperatures and below.

6.7 Analysis: Credible Expectations

In the process of enacting and selecting technologies on the basis of expectations, three elements appear to be vital to the construction of credible expectations. First there is the technology's current level of performance and its historical progress towards that level. Second a path forward is constructed to argue that even higher levels of performance can be achieved. And third, a target or end-goal is constructed that the technology is expected, or supposed, to meet and this end-goal relates to some perceived need or opportunity. All three elements can, and often are, subject of contestation. The performance of any technological option might be disputed as a result of different measurements. And relevant performance criteria can be subject to debate as well: for different options, different performance measures may be more or less favourable. The path forward is constructed on the basis of assumptions with regard to theoretical and practical arguments and these assumptions can be called into question. And the end-goal is not necessarily shared between all stakeholders. Furthermore there are competitors that also have their promises and link up with the same societal needs. In this section we analyze the process of expectations assessment as it has taken place within the Hydrogen Program according to these three elements of credible expectations. The construction of credible expectations is depicted schematically in Figure 6.5.

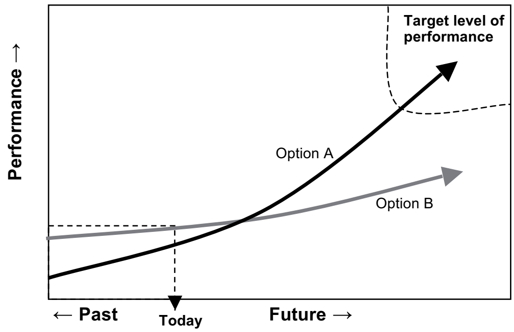

Figure 6.5 The construction of a credible expectation of technological progress: a path is constructed from today's level of performance (on different and often contested criteria) and recent progress of 'Option A' to a more or less broadly defined target in a given timeframe. This is done for the enacted technological 'option A' and at the same time it is argued that competing 'option B' can not meet that target.

Current performance and progress

Even though technological expectations are about what is to be achieved in the future, arguments about earlier achievements are very much part of expectations work. For the members of HTAC, it proved to be more and more important to get across the current performance levels of hydrogen technologies and their proven viability in early markets. With increasing pressure from the selectors, either because of political pressure from the Secretary in the final months of his term, the credit crunch or the rise of competing solutions such as the plug-in hybrid vehicle, hydrogen needed to be reconstructed as a short term option. As a result, the enactors started to stress that hydrogen is not only an option with great potential for the long term, but also something that is very much happening today: in early niche markets such as forklifts and in test programs with fleets of hydrogen vehicles; fuel cells are reliable and high-pressure storage suffices. Also, with the new Secretary the HTAC members felt that they had a role in educating him with regard to the enormous progress in hydrogen technology in recent years. The role of past progress is perhaps even more visible in the assessments that the DOE makes in its capacity as technology selector. Any option that continues to make progress is assured of continued support whereas those options that show stagnation are scrutinized and face the risk of a no-go decision.

What measures of performance should be seen as critical and decisive is contestable. In the case of the no-go decision for on-board reforming of methanol, it is not so much the drive range of the vehicles that is most critical, but rather the overall energy-efficiency and emission levels. Such a vehicle would outperform any other hydrogen vehicle in terms of range, but it does not deliver the so desperately desired low-emission vehicle.

Path forward

To argue that a technological option has a credible chance to improve even further, an extrapolation of the recent progress is often the starting point: the fact that progress was possible in the past implies that further improvements are as well. On top of that, extra arguments can be provided to convince the selectors that there is indeed a path forward. In such an argumentation, a lot depends on the theoretical potential of the technological options. For instance, fuel cell costs can be lowered with smaller amounts of platinum catalysts. The costly platinum is needed, but in theory the fuel cell could do with less catalyst material: only a very thin layer is needed. To realize this potential, different production methods need to be developed to apply thinnest possible layer of platinum without compromising its capabilities as catalyst. In other words, there is a path forward, but it depends on further engineering whether this path can be realized. The same holds for the doped carbon nanotubes. In theory they can store high percentages of hydrogen (given the space available in the material's cavities), but a lot of work is needed to achieve those percentages at acceptable temperatures, at large scale, against reasonable costs and in practical applications for every day use.

In the case of on-board fuel processing such a pathway could not be identified and no credible expectations could be constructed: the end was in sight and other options already outperformed this option. A credible path forward thus builds on a theoretical potential and an engineering approach to realize the potential: first under laboratory conditions and second in real-use situations and finally at commercial costs and scale.

Targets and goals

Targets and goals are very much a part of the enaction and selection process and are therefore a necessary element in any credible expectation, be it explicit or implicit. In the case of hydrogen storage, the DOE has set explicit targets that are supposed to be met in a given timeframe. These targets are used to assess the progress and credibility of the different storage options. However, the more specific the targets are, the more fallible they are (van Lente 1993) and targets are, just like performance measures, subject to contestation. In the case of the storage targets, it is debated to what extent the targets are realistic and whether the targets really need to be as high as they are. As described, the targets were lowered to accommodate for new insights in the fuel efficiency of hydrogen fuel cell vehicles. The same goes for the desired cost price of vehicular fuel cells: there is a target for fuel cell systems (set at $30/kw, making for a $3000 fuel cell in regular cars) and it is debated whether or not this is realistic and whether or not the price actually needs to go down.

For the more abstract goals, such as the reduction of CO_2 emissions, the security of energy supply, and economic progress, the targets are less clear. Nonetheless, these goals are very much part of the enaction process and especially in the deliberations of the HTAC the role of hydrogen in the development of the US economy plays a major role. Here it also stressed that other selectors have or will select the hydrogen option to meet their goals and that the US should not fall behind with the other countries and foreign car manufacturers.

The competing options

At least in the case of hydrogen technologies, expectations of one option are always related to the expectations of another option. Selectors have a number of available options they can choose from and it is up to the enactors to convince them that the other options are not as promising as their own. For instance, metal hydrides are promising because they have a path forward but at least as important for the metal hydrides community was and still is the notion that its competitors do not have such a path. And, again, on-board reforming was no longer promising enough as soon as it was shown that plug-in hybrids were already delivering the same efficiency and low emissions. And because hydrogen is competing, on the vision level, with these plug-ins and other options, it was decided that it was in the interest of the hydrogen vision to out select this underperforming option.

Competing options are likely to perform different on different measures. Competing enactors will therefore stress those performance measures that are most favourable to their solution. For instance, enactors of on-board reformers will stress the importance of long drive-ranges, as these perform well on that measure as compared to other solutions. Likewise, the enactors of carbon nanotubes have put more emphasis on safety as their option scores well in that respect.

And furthermore the challenge was to get hydrogen out of the long-term perspective and move it into the short and mid-term perspective, especially because plug-in and biofuel vehicles were seen as much more short term options and were "chipping away" funding from hydrogen. To stress the short term perspective of hydrogen technologies, the community put more and more emphasis on hydrogen's accomplishments in its early niche markets such as forklifts.

6.8 Conclusions and discussion

We have studied the enaction and selection of emerging technologies on the basis of expectations. Special attention was given to the notion of credible expectations: why are some expectations thought to be credible and why are others not? From both the enactors' as well as the selectors' perspective the same type of constructions seem to be made. In conclusion we state that credible expectations build on current performance and recent progress, the identification and construction of a path forward and a target performance level that the technological option is supposedly able to meet. The construction of the path forward is perhaps the most critical to the credibility of expectations. This path is constructed on the basis of theoretical potential of the option (what is ultimately possible?) and a route for engineers to fulfil that potential. The construction of a credible storyline for the future potential of a technological option is useless however, when the associated community of enactors is unable to get the story across to its selectors. The disappointment that surrounded hydrogen after its period of high hopes and overpromising made that HTAC was no longer able to communicate its message to the higher levels of the Department. Even something as mundane as a letter to the secretary was now problematic and setting up a meeting proved impossible altogether. The credibility of technological expectations as such can thus not be uncoupled from the credibility of the associated community, stressing again the role of agency in both the construction and the assessment of technological expectations.

We made a distinction between enactors and selectors in order to study the agency that is involved in the shaping of collective expectations. But this distinction is not so much a distinction between fixed positions, but rather a distinction between two roles that actors can play in the innovation process. As we sketched earlier, selectors may become enactors once they have selected a technological option. And in the case of a hierarchical build up of an emerging sociotechnical system, an actor that enacts the system can be a selector with respect to underlying enabling technologies. We have witnessed that, in the latter situation, the processes of enaction and selection are very much interrelated. With increasing doubts over hydrogen as fuel of the future, i.e. the hydrogen vision being more difficult to enact, the selectors' role of the HTAC became more prominent. Whereas the HTAC could support a wide variety of technological options in its early meetings, in the later meetings more and more pressure was felt to decrease the number of options under study. The problem of hydrogen storage was said to be solved with the 700 bar cylinders for instance and this relieved the hydrogen vision of one of its necessary 'miracles'. It is thus not only the scarcity of resources that hydrogen was facing, but also a matter of reducing the number of perceived problems that surrounded hydrogen. And, for a contested vision such as hydrogen the process of technology selection is not so much one of *picking winners* (Irvine and Martin 1984), but rather one of *dropping losers*.

The sociology of expectations deals mainly with collective expectations as structures which individual actors have to take into account in their decisions and actions. In this paper the focus was on individual agency in the enaction and selection of forceful expectations and that makes for a distinctly different level of analysis. The choices that are made and the targets that are set within the DOE Hydrogen Program are an important point of reference for the global hydrogen community. In that sense the DOE is an important source of expectations that become collective. By zooming in on the processes of enaction and selection within the DOE we were able to explain the emergence of such collective expectations. Yes, innovation processes may be stimulated, steered and coordinated through a dynamic set of collective expectations, but it is these processes at the level of highly influential actors and organizations the forceful collective expectations are shaped and voiced.

7. The cars of the future – hydrogen versus battery-electric

7.1 Introduction: technological niches and competition[41]

In innovation studies, the concept of 'niche' has become one of the building blocks to account for the occurrence of radical innovation. Drawing on an evolutionary metaphor, the concept of niches has been proposed in the 1980s to explain why and how the stability of existing technological trajectories can be breached by radical innovations (Vergragt 1988). The dynamic stability of established technologies is expressed in technological trajectories, which gain their stability from 'technological paradigms' (Dosi 1982) and 'regimes' (Nelson and Winter 1982). Progress along these trajectories is limited to cumulative and continuous change, while discontinuous change is discouraged in two ways. First, stability of existing paradigms, regimes or trajectories is the result of self-reinforcing (socio-)cognitive frameworks that allow for incremental improvements, but shut out more radical and divergent innovations. That is, engineers, managers and policy makers share a set of heuristics that guides them along the existing path and makes that they do not explore beyond known territory. Second, the 'selection environment' tends to prefer existing solutions, due to economies of scale and lock-in effects (David 1985, Abernathy and Utterback 1978), and is thus hostile to new, diverging solutions.

Consequently, radical innovation and the emergence of a new technological regime will only take place *outside* the existing technological trajectories (van den Belt and Rip 1987, Dosi 1982). The concept of 'niche' has been introduced to explain the dynamics of radical innovation. The basic idea is that niches protect new developments (or technological variations) against the hostile forces of its established selection environment: the protection might be in the form of funding, legitimation and other resources (Kemp et al 1998, Schot and Geels 2007). These niches should not be confused with

41 This chapter is submitted for publication and is co-authored with Harro van Lente and Remko Engels

the well-known market niches in marketing studies: specialized markets for a dedicated group of users. In contrast, technological niches account for the generation and development of new technologies. The niches act as incubation rooms that provide the infant technology with attention, legitimacy and funding: they shield new technologies with their low initial price/performance ratio from selection pressures, allowing them to develop and mature (Geels and Raven 2006, Verbong and Geels 2007). In other words, in a technological niche, technological variations that are promising and desirable but not mature enough for market selection are developed further up to the level that they can compete with the existing regime technology.

Nowadays, the concept of 'niche' is well-established in studies of technical change. Many studies on niches are concerned with energy related technologies (Lopolito et al 2010, Raven and Geels 2010, van Eijck and Romijn 2008, Agnolucci and McDowall 2007, van der Laak et al 2007), but also with mobility (Schot et al 1994, Ieromonachou et al 2004), sanitation (Hegger et al 2007), housing, and the food sector (Smith 2007). These studies have yielded insights into the actual processes that take place within a niche and how a niche (competitively) relates to its respective regime. But it is less clear what happens when *multiple* options are simultaneously challenging the existing regime. Will there be multiple niches? How do these niches interact? How do these interactions actually affect the overall developments (Markard and Truffer 2008, Smith et al 2010, Schot and Geels 2008)? Two papers that addressed these interactions focused on the complementarities of multiple niches (Nykvist and Whitmarsh 2008) and, respectively, on patterns of succession of different niches in terms of attention and expectations (Verbong et al 2008). Yet, the question remains: what happens when *more options* are available and explored at the same time and that these *compete* for attention, legitimacy and funding[42]? We argue that it is likely that such situations occur and are relevant to study.

In this paper we aim to contribute to the understanding of niche dynamics in the case of competing radical innovations. More specifically, our case deals with two of the main options - battery-electric and hydrogen vehicles - that oppose the incumbent regime of car manufacturing. We investigate how these options share a niche for the 'car of the future', how they both challenge the existing paradigm and at the same time fiercely compete amongst each other for R&D funding, favourable regulation, tax incentives and infrastructure build-up. Central to our analysis is a focus on design rules and expectations as major indicators of niche developments. Our study draws from an analysis of developments in the global automotive sector between 1990 and 2010. Before we present the results of our case study, we will first have a closer look at what constitutes a niche and its internal dynamics.

42 The same goes for the strand of literature on technological innovation systems (TIS), which tends to focus on the development processes of single technological options and to ignore the interaction between (competing) systems.

7.2 Global and local niches for competing technologies

In general, radical innovations have a hard time to survive. Sometimes, however, when the sociotechnical landscape allows, windows of opportunity for radical change may be created (Geels 2002, Geels and Schot 2007, Raven 2004). Such susceptibility may be, as in the case of the car of the future, related to the environment or concerns over the availability of natural resources. Radical innovations can profit from these windows and attempt to breach the existing regime. Often this proceeds through a process of accumulation of local niche activities in which these innovations are used in subsequent application domains and in which they enter increasingly bigger (market) niches (Geels 2002, Geels and Schot 2007). The process of niche-accumulation emphasizes that a niche should not be seen as an isomorphic phenomenon, but as an interconnected set of smaller, local niches which eventually may jointly shape a new regime. Such interconnection of niches does raise conceptual questions though. Is the niche to be understood as the localized and context specific protection of an individual pilot or demonstration project, or as the wider protected space that enables a host of local projects? Geels and Raven (2006), and similarly Geels and Deuten (Geels and Deuten 2006), propose to distinguish between a local and global level in a niche: the *local* level then consists of a variety of local projects that are carried out within individual firms or organizations, while at a *global* level an emerging technological trajectory in general is shielded. They add that the distinction between the two levels of niches highlights the cognitive difference between, on the one hand, local design rules and expectations and, on the other hand, collective design rules and expectations that are shared among projects, firms and governments (Geels and Raven 2006).

The dynamics of niche-accumulation is, then, not just the accumulation of local projects, artefacts and early niche-markets, but rather a socio-cognitive accumulation of *design rules* and *expectations*. The first relates to the different design options within the new technology that are gradually articulated into shared design rules that prescribe how the technology can be put to work in the most effective and favourable manner. The second, the set of expectations, plays a particularly important role in the early phases of technological development, when uncertainty is highest regarding the future potential of technologies and their future selection environment (van Lente 1993, Borup et al 2006, Guice 1999). The build-up of technological niches is very much the result of expectations of future societal and market needs and the performance potential of the technologies that are being developed: there is a perceived gap that needs to be filled and there are technological options that are thought to be able do so. Expectations of both the problem and the solution are held by industry actors and/or policy makers and the more widely acknowledged (or collective) and specific they are, the more powerful they are (Konrad 2006). The significance of collective expectations widely been recognized in the literature on technological niches (Geels 2002, Geels and Raven 2006, Geels and Schot 2007).

In the case of competing technologies, it is thus important for any of the contenders to be surrounded with collectively shared positive expectations. Local projects and experiments can build on each other (in terms of experiences, practical results, and legitimacy) and gradually add up to an aggregated level where expectations are more articulated, stable, and specific (Geels and Raven 2006). The same goes for design rules. Various design rules can be applied in different local contexts, but over time they might also aggregate and converge to more articulated and widely shared design rules throughout the global niche.

To sum up our argument, we highlight here four points that we take from the review above:

- emerging technologies require niches in which they are protected from direct market selection;
- multiple technological options may be developed simultaneously and might compete amongst each other;
- within niches, a distinction can be made between a local and a global level;
- competition between options will take place in terms of design rules and expectations about future performance of technologies: for any option to be successful it needs to build on well articulated design rules and be surrounded with collectively shared positive expectations.

7.3 Case selection and methodology

Throughout the automotive industry, firms develop cars that can meet future emission standards and anticipate higher gasoline prices (Oltra and Saint Jean 2009, Frenken et al 2004). First of all, a so-called sailing-ship effect can be recognized in the attempts to improve efficiencies of conventional combustion engines and drivetrains, for instance by introducing start-stop technology and regenerative breaking (Dijk and Kemp 2010). Second, work has been done and is on-going on biofuels and natural gas. These options do not rely on radical changes in the design of the vehicles, but can contribute to lower emission levels on a well-to-wheel basis (Suurs 2009). Somewhat more radical is the hybrid vehicle, a combination of the conventional design with electric drive to varying extents. Our study focuses on two radical solutions. Both hydrogen and battery-electric vehicles are zero-emission vehicles from a tail-pipe perspective and step away from hydrocarbon based fuels altogether. They are competitors, but at the same time they compliment each other as well (van Bree et al 2010). Most hydrogen vehicles, as we will discuss later, are in essence electric cars with a fuel cell instead of a battery. However, in terms of powering the vehicles, there is a fundamental difference between charging the car from the electric grid and fuelling the car with hydrogen. Both options thus rely on different infrastructures and one can question if both can be developed at the same time given the needed capital investments. Already in the 1980s, Callon (1980) discussed the competition between these options likewise in terms of the French state deciding to support either the one or the other.

For all these radical options some protection is provided. Governments fund research programs and set up regulation to change the selection environment for automobiles. The industry supports efforts in R&D departments and engages in demonstration and testing projects. Often, these various protective acts have reinforced each other and gave rise to local niches such as those often studied in early Strategic Niche Management literature (Schot et al 1994, Hoogma 2002) as well as to a global niche of the 'car of the future' that welcomes various specific attempts. That is, within the overarching protective space multiple local niches are created in which different technologies are developed.

To investigate the co-existence as well as the competition between battery-electric and hydrogen vehicles within the broader niche, this study will follow the car manufacturers and their local niches as well as the industry wide global niche. We will trace both the various local expectations and design rules and the more abstract, generic expectations and rules that are shared within the car industry at large.

Our data source is a leading weekly car magazine in the Netherlands in which many of the industry's efforts towards both battery electric and hydrogen vehicles are covered: *AutoWeek* in the period 1990 – 2009. *AutoWeek* was chosen as it is the well-read and top car magazine in the Netherlands and all issues in the given period (≈1000) were available for our analysis. As a car magazine for the general public, it contains background articles as well as reports from international car shows. To collect the data, each edition of the magazine was checked for items that related to electric or hydrogen vehicles. We triangulated our findings with the Dutch edition of *Top Gear Magazine,* from 2005 onwards, to check for any magazine-specific bias. Furthermore, we found no reason to assume any country specific bias. As the Netherlands is by and large not a car manufacturing country, we assume that there is no bias in Dutch media towards any of the car manufacturers or their technological options.

The analysis includes the technological choices of individual firms to distinguish the specific technological trajectories that the firms have chosen to follow in their local practices. The different trajectories represent the variety of design rules for the 'car of the future'. Whether or not these converge throughout the industry is then an indicator of the emergence of aggregated rules at the global level. For the electric vehicle, for instance, there is a range of electric batteries that can be used, such as lead-acid, nickel-based and sodium-based batteries (van den Bossche et al 2006). Then, for the hydrogen vehicle there are also different technological options for both the hydrogen storage method and the energy conversion method (Bakker 2010). Furthermore, hydrogen can fuel both an internal combustion engine vehicle and a fuel cell vehicle and there are different types of fuel cells as well. In Figure 7.1 we schematically show the hierarchy of technological options, from the overarching generalized 'car of the future', down to specific design options for both hydrogen and battery-electric vehicles.

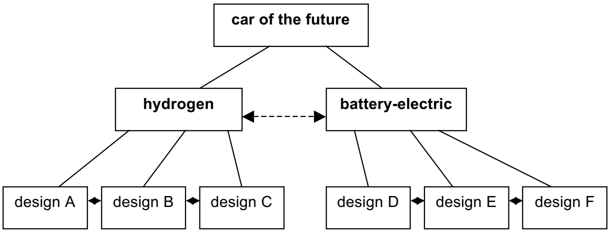

Figure 7.1: Hierarchy of competing technological options and accompanying competing expectations for the car of the future

7.4. Results

In the *AutoWeek*, the numbers of articles on battery-electric and hydrogen vehicles have been relatively stable throughout the 1990s. Starting around 2003, the numbers increase rather sharply and the cars of the future are clearly surrounded with high expectations. Interestingly, the distribution of attention between the two shows clear shifts from the one to the other (as displayed in Figure 7.2).

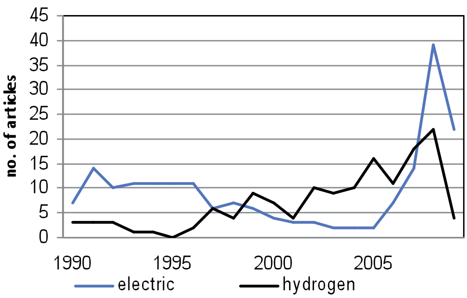

Figure 7.2 The numbers of articles on battery-electric and/or hydrogen technologies in Autoweek, 22 January 1990 - 31 March 2009

During the early 1990s the niche is dominated by battery-electric vehicles. Then, by the end of the 1990s the leading position is taken over by hydrogen cars. That lasts until 2005 when electric cars start to regain their dominancy. In Figure 7.3, the differences in the numbers of articles are visualized and the shifts in attention become even clearer. Dominancy however has never been complete for either of the options. At all times, there has been at least some attention for the other option as well.

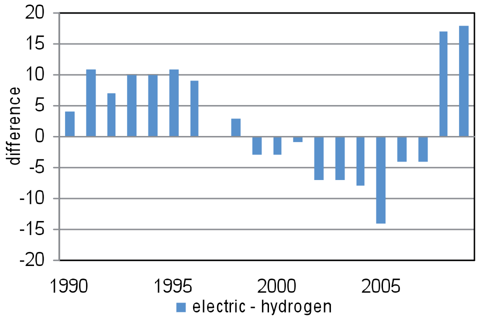

Figure 7.3 The difference between the numbers of articles on battery-electric and hydrogen cars, 22 January 1990 - 31 March 2009

In the following we try to reconstruct the competition between the options in these three phases. The emphasis is on the role of design rules for both options and the accompanying technological expectations as voiced in the firms' statements.

1990-1997: exploring batteries

Electric

Between 1990 and 1997, no less than 47 battery electric vehicles were presented to the general public. These vehicles were developed for several reasons: most of them for experimental purposes, others to evaluate market needs or to investigate potential technological barriers. Cars such as the Fiat Panda Elettra, the Peugeot J5 Electrique, and the Mini-El were actually introduced on the market in limited numbers. GM leased a number of its Impacts (the predecessor of the EV1).[43]

The strongest incentive for the industry to develop electric vehicles was provided by the Californian Air Resources Board. Its zero-emission regulations required all firms active on the Californian market to offer a zero-emission vehicle. While the car industry protested against these regulations and claimed that the electric vehicle would not be commercially viable[44], they did respond with a number of models.

The biggest challenge was to develop car with acceptable ranges between recharging and many different battery types were experimented with. In the earliest models, most firms chose the lead-acid battery as storage medium as it was the cheapest and best-known battery available. In later vehicles, the scope broadened and other battery-types were used such as sodium-sulphur, nickel-salt, and nickel-cadmium batteries, and also the use of ultra-capacitors was considered.[45] From 1995 onwards,

43 AutoWeek, 1994, No. 52, pp. 18-21.

44 AutoWeek, 1995, No. 8, pp. 30-31.

45 AutoWeek, 1994, No. 44, pp. 46-47.

nickel metal-hydride batteries were used. A car industry outsider, Samsung, stated in 1994 that it was working on the most promising battery option for vehicles: the lithium-ion battery. Samsung claimed to finish the development of these batteries by the year 2000.[46]

From this wide variety of battery types, no clear winner stood out. At the global level of the niche, expectations diverged as these all hinged on the capacity of the batteries. Despite the large numbers of experimental vehicles, firms were openly questioning the future of the electric car. One example of such doubts is found in GM's Vice-President John F. Smith Jr statement: "*The battery electric vehicle is of course not the ideal solution. The electric vehicle could, however, be a good alternative in cities and urban areas, which could improve the quality of living in these areas.[…] Without a big breakthrough in the field of electric batteries, the electric vehicle will not succeed and we will not progress beyond producing an improved version of a golf cart.*"[47]
No breakthrough was realized however and when, in 1996 a group of manufacturers including GM, Ford, Chrysler, Toyota, Honda, Nissan, and Mazda managed to have the CARB regulations[48] cancelled, the battery electric car lost its dominancy in the niche.

Hydrogen

Only nine hydrogen vehicles, by six different manufacturers, were presented to the public in this period. None of these were produced in anything like series or released onto the market. In its early years, many options were explored for hydrogen storage as well as conversion. Local solutions were sought by different firms and each was accompanied by different expectations. The issue of hydrogen storage is very much similar to that of the batteries in electric-vehicles as both limit the range of the vehicles. Daimler had high hopes of high-pressure gas cylinders, BMW and Renault attempted to store liquid hydrogen in cryogenic tanks and Mazda and Toyota have used metal hydride tanks. Satisfying ranges were not realized however and energy efficiencies and safety concerns remained problematic as well.[49] [50]
For hydrogen conversion, Mazda and BMW relied on the combustion engine. Mazda did so because it wanted to use is rotary engine and BMW was concerned that only ICE's could provide enough power to satisfy its customers. The majority of firms chose to use (PEM) fuel cells as these were able to deliver higher efficiencies without any emissions.

As all manufacturers were struggling with range requirements, it is no wonder that developers of one option criticized the others' solution. Helmut Werner, of Daimler, for instance stated that: "*We are ahead of anyone in the world with the development of the fuel cell. The electric vehicle will never amount to*

46 AutoWeek, 1994, No. 45, p. 6.

47 AutoWeek, 1991, No 52, p. 19.

48 AutoWeek, 1996, No. 4, p. 6.

49 AutoWeek, 1990, No. 18, pp. 2-3. AutoWeek, 1997, No. 5, p. 8.

50 AutoWeek, 1990, No. 18, pp. 2-3. AutoWeek, 1997, No. 5, p. 8.

anything and neither will hydrogen driven combustion engines".[51] By the end of this period, the battery-electric vehicle had disappointed and hydrogen gaining momentum in the niche. The allure of the fuel cell and new and promising means of storing hydrogen suggested that hydrogen cars could only get better. Many governments encouraged their industry to develop hydrogen technologies. Most striking in that respect was the 1993 US government initiative to invest 1 billion USD in the development of a clean fuel cell vehicle. It composed a research team consisting of General Motors, Chrysler and Ford[52] Other cooperative efforts were made in Europe and Asia as well: Daimler together with Mazda[53] and once again Daimler with Ballard Power Systems to develop the Necar I and II.

1998-2005: the rise of hydrogen

Electric

During the following phase, only 14 battery-electric vehicles were presented to the general public. The drop in attention in the industry is probably caused by limitations, including range and costs, of the batteries. The firms that did continue the development of electric cars were rather active nonetheless. Nissan, for example, presented the prototype Altra EV in 1998. Around 30 vehicles were tested in California, while Nissan further stated that it would be available for the general public in the year 2000.[54] Honda presented the EV-Plus, of which a fleet of 100 vehicles was tested in the Mendrisio project in Switzerland.[55] Then, in 1999 one battery electric vehicle was actually produced for commercial use: the Th!nk, a product of Ford and Norwegian Pivco.[56] [57] In 2002 however, Ford pulled out of the project because of disappointing sales numbers.[58]

Despite the globally shared expectation that battery technology was still not mature, a smaller number of battery types was used in this period: design rules started to converge to nickel-cadmium and nickel-metal hydride batteries. And the most promising option was still to be used: the li-ion battery. This type was said to be expensive, but also lighter and with higher energy densities as compared to nickel-cadmium and nickel metal-hydride batteries.[59] On the basis of high hopes of li-ion batteries, a number of car makers openly spoke of market-entry. Renault announced an electric version of the

51 AutoWeek, 1996, No. 26, pp. 28-30.

52 AutoWeek, 1993, No. 19, p. 7.

53 AutoWeek, 1992, No. 35, p. 6.

54 AutoWeek, 1998, No. 5, p. 54.

55 AutoWeek, 1998, No. 38, p. 7.

56 AutoWeek, 1999, No. 4, p. 10.

57 AutoWeek, 1999, No. 4, p. 10.

58 AutoWeek, 2002, No. 40, p. 8.

59 AutoWeek, 1998, No. 5, p. 54.

Scenic[60] and Smart announced that it would work together with eMotion Mobility to develop the Smart City-Coupe.[61] The bulk of the industry did not subscribe to these high hopes though.

Hydrogen

While the future of electric cars was questioned by many, the hydrogen car had emerged as the new favourite option in the niche. 33 Hydrogen prototype vehicles were presented in this period and all major car manufacturers were involved. Initially there were no shared design rules and some firms developed fuel cell cars while others stuck to combustion engines. Gradually this changed and the designs converged by and large towards a single design of fuel cell and high-pressure storage. Some firms remained divergent though and BMW and Mazda held on to their ICE designs, and BMW and GM continued to work with liquid storage.[62] [63]

In general, the car industry now seemed rather optimistic about hydrogen vehicles and many statements about market entry can be found in the *AutoWeek* articles. Opel President McCormick stated: "*I expect no serious barriers on the road to producing vehicles in series. Our goal is to be ready for launching fuel cell vehicles in 2004*".[64] Moreover, at the same time Opel predicted that within ten years 10% of their vehicles to be sold would be fuel cell vehicles[65]. Similar statements were made by Daimler[66], Nissan[67] [68], Toyota[69], GM[70], and KIA.[71]

On average, manufacturers promised to start production within 5 to 6 years, but as these promises were not met, hype gave way to disappointment. To illustrate, in 2001 Opel realized that it would not be able to launch the hydrogen vehicle in 2004, after which they stated that fuel cells would not be ready for mass production for another 10 years. Often, the delayed introduction of the hydrogen vehicle was attributed to the lack of a hydrogen refuelling infrastructure. But some firms acknowledged that their vehicles were not ready yet. Again to illustrate, Gerd Arnold of Opel: "T*he storage of hydrogen in tanks is somewhat complicated. We are not there yet, but we are getting closer*".[72]

60 AutoWeek, 1999, No. 8, p. 11.
61 AutoWeek, 2001, No. 41, p. 6.
62 AutoWeek, 2003, No. 25, p. 29.
63 AutoWeek, 2003, No. 25, p. 29.
64 AutoWeek, 1999, No. 2, p. 9.
65 AutoWeek, 1999, No. 2, p. 8-9.
66 AutoWeek, 1998, No. 20, p. 7.
67 AutoWeek, 1999, No. 26, p. 8.
68 AutoWeek, 2002, No. 33, p. 8.
69 AutoWeek, 2001, No. 45, p. 7.
70 AutoWeek, 2002, No. 36, p. 8.
71 AutoWeek, 2005, No. 20, p. 8.
72 AutoWeek, 2003, No. 25, p. 29.

2006-2009: the revival of electric

Electric

Since 2005 the electric vehicle has made a comeback in the niche and from the year 2008 onwards the majority of statements are in fact again about electric technologies. The number of battery electric prototypes has also risen sharply to 34 in only three years. These vehicles were developed by both large manufacturers and small new-entry firms. Among the large car manufacturers were Mitsubishi, Audi, BMW, Nissan, Renault, General Motors and Toyota. Whereas Tesla can be considered the frontrunner of the new industry that might arise for the electric vehicle, other new manufacturers such as Ruf and NICE (No Internal Combustion Engine) also promised to enter the market with their cars.

Numerous car manufacturers promised to introduce an electric vehicle within years. And despite some critical remarks about the performance of lithium-ion batteries, the car industry did finally converge to a single battery type. A number of problems were still said to require attention. For instance, Volkswagen stated that "*a large part of the research- and development work still has to be done before we can produce a vehicle, especially in the field of lithium-ion battery technology.*"[73] And, similarly, Daimler stated that "*the battery technology is still problematic: especially the weight of the batteries… There is a lot of hope, but this cannot be based on the state-of-the-art in the field of battery technology*".[74]

Hydrogen

Even though production goals for hydrogen cars were pushed forward and the electric car made its comeback, by the end of this period hydrogen was still considered as an alternative for the long term. On the global level of the niche hydrogen had lost credibility, but at the local level 23 hydrogen vehicles were nonetheless developed and presented to the general public.

As discussed above, market-entry promises had not been realized and manufacturers had toned down their promises and expectations. Daimler, Honda, and BMW did engage in large scale testing programs with hundreds of vehicles, but the tone was different. Nonetheless, some firms did continue to make promises about market-entry. In 2007, KIA stated that it wanted to have a hydrogen vehicle ready for production in 2012, but at the same time it questioned whether this would be commercially available.[75] Then, in 2009 Mazda stated that the engine driven vehicle RX-8 Hydrogen RE could be ready for production in 2012.[76]

More common, however, was the expectation that it would take another 10 to 20 years for hydrogen vehicles to be ready to for mass production. Volkswagen was even less optimistic and had higher

73 AutoWeek, 2009, No. 14, p. 27.
74 AutoWeek, 2008, No. 10, p. 45.
75 AutoWeek, 2007, No. 21, p. 64.
76 AutoWeek, 2009, No. 5, p. 43.

hopes of the electric vehicle. In his statement, Seyfried, Director of Volkswagen's Powertrain Fuel Cell Department, underpinned the competitive relation between hydrogen and battery-electric vehicles: "*Honestly, I do not know if we will ever need the fuel cell. If the development of electric batteries continues to progress in the current tempo, this might not be the case.*"[77].

7.5 Analysis and Conclusions

The concept of 'niche' is an important contribution to our understanding of technical change and especially of the competition between existing socio-technical regimes and the challenging radical innovations. A niche is the set of arrangements to protect novel technologies and to provide them with attention, legitimation and funding. However, it is less understood what happens when multiple emerging technologies together challenge the regime and, at the same time, compete with each other. Such a competition challenges current conceptualizations of technological niches and raises the question whether these options are protected separately, in competing niches, or whether they both occupy the same niche and compete within that one niche. How do these novel technologies, in interaction, develop within the various forms of protection? What happens in these sets of niches?

In this paper we started with a distinction between local niches for specific solutions and a generalized global niche. We have traced how two niche technologies in the car industry, that both challenged the existing regime, were also in competition with each other. The pressure on the car industry is to develop an alternative, low- or zero-emission, design to replace the current internal combustion solution. As a consequence, a niche for the 'car of the future' is sustained and the extent to which the options are expected to meet those standards, determines which of the options gets most attention and receives most protection: which gets the best position under the umbrella.

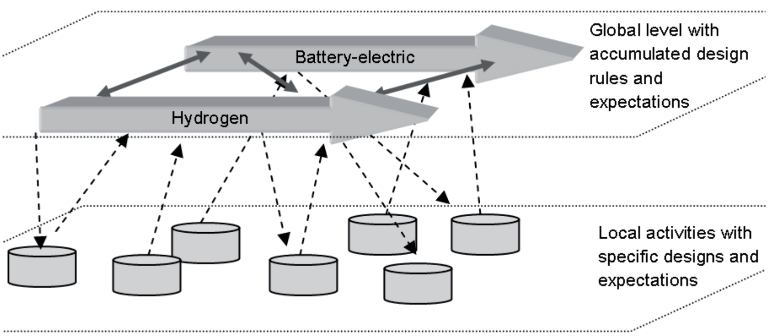

Figure 7.4: the local and the global level of the niche for the car of the future

We analyzed the competition between the options and started from the distinction, following Geels and Raven, between a global industry-wide level of the niche and local level of specific manufacturers

77 AutoWeek, 2008, No. 27, pp. 20-21.

and projects (Figure 7.4). We traced the dynamic in and between these two levels by following design rules and expectations in the period between 1990 and 2009 in the complete set of printed issues from that period of a leading Dutch car magazine *AutoWeek*. We confirmed that the joint efforts of car manufacturers and governments resulted in a global niche in which two technological options compete: hydrogen versus battery-electric vehicles. Within that protected space, many local efforts are undertaken by car manufacturers. Almost without exception, all firms work or have worked on both hydrogen and battery-electric vehicles at some point in time. However, there have been apparent shifts between the two options. This was clear from the number of statements that the car manufacturers have made and this is paralleled by the numbers of prototypes the car manufacturers have shown to the public. Table 7.1 gives an overview of the numbers of prototypes in the three phases.

Table 7.1: Numbers of prototypes mentioned in *AutoWeek*

Phase	Battery-electric	Hydrogen
1990-1997	47	9
1998-2005	14	33
2006-2009	34	23

From the local efforts throughout the industry, distributed in time and space, more general and collectively shared design rules and expectations have aggregated at the global level. The design rules can be seen to diverge and converge during the different phases for both battery-electric as well as hydrogen vehicles. Eventually, for both options the industry seems to have converged to designs that are adopted by almost all firms. From the wide variety of design options and expectations in the 1990s, the li-ion battery and the fuel cell and gaseous storage designs have emerged. As for the battery-electric cars, the analysis shows that at first, in the early 1990s, a wide variety of designs (i.e. different types of batteries) were used. That variety indicates an explorative stage of development, but at the end no single battery type could deliver the desired performance. As a result of that generally shared expectations were low and eventually the car industry decided to stop most of its efforts. To paraphrase the sentiment with regard to battery-electric vehicles in those days:

> *"We have tried everything, but nothing seems to work"*

The battery electric car was not deemed viable at that time. Given that the niche for 'car of the future' was still sustained, the initial disappointment with battery electric vehicles made way for the hydrogen car: it opened up a window of opportunity. Similar to the use of different battery types, for hydrogen a wide variety of technological options were explored. From that multitude of explorations, the local firm niches have gradually converged to a design rule that is adopted by almost the entire industry. Yet, the resulting technological trajectory, a hydrogen fuel cell in combination with gaseous storage, did not lead to globally shared high expectations. The expectations of hydrogen vehicles seem to be rather unstable at the end of the hydrogen phase and can be paraphrased as:

"We know what works best, but we're not sure if it's good enough"

The lack of collective positive expectations of hydrogen technologies was followed by a return of the battery-electric vehicle. This, in combination with the (rather silent) progress of the Li-ion battery, has resulted in renewed expectations of the battery option. The current notion in the global niche now seems to be:

"At last we have found the right battery and this one is good enough"

The relation between battery electric and hydrogen vehicles is thus indeed competitive: it is either battery electric or hydrogen. Both options share the same global niche, but only one is dominant in the niche at any point in time. Interestingly, most car manufactures have worked on both options and governments impose regulations that favour zero- or low-emission vehicles in general, but not one of the options in particular. Yet, these actors need to divide their resources over the two options, which may result in a 'winner takes it all' strategy. Under such conditions, the competition for funding and the shifts in attention and expectations that we have witnessed does have an impact on the development trajectories of both options. After the first peak of activity with electric vehicles, much of the funding was taken away from that option by both firms and governments and efforts were put to a hold. The same goes for hydrogen vehicles after an apparent lack of progress. These ups and downs are most probably detrimental to the development of both options and it is no wonder that many advocates call for something like *expectations management* surrounding their option, to avoid these dynamics of hype and disappointment. On a rather speculative note, one could doubt whether such expectations management is possible at all given the ongoing dynamic of expectations (van Lente and Bakker 2010). The engineers and other members of the respective technological communities need to explain their sponsors why their option is promising why support is thus legitimized. For them there is hardly reason to be modest as they need all the support they can get and this is done best with high expectations and bold promises. The risk of overpromising and the subsequent backlash of disappointment are necessarily taken for granted.

Perhaps it is more a task of the technology supporting actors and organizations to manage their own expectations and refrain from choosing sides in the competition all too hastily and drastically. In other words, they should cherish variation, rather than side with the provisional winner (Schot and Geels 2008, Luiten et al 2006). Promising, in that respect, is the fact that the EU continues the development and deployment of hydrogen vehicles through its Joint Technology Initiative (JTI) and the fact that hydrogen budgets in the US were continued despite the Energy Secretary's disbelief and general disappointment after the hydrogen phase. Whether these continuations are the result of a deliberate strategy or merely the result of slow policy making is debatable. The JTI, for instance, was initiated in

2003 and became effective only in 2008 and it would be difficult to initiate such a program in a phase of low expectations. Nonetheless, both the EU and US continuations of funding provide an opportunity for the hydrogen community to continue their work at the various local niches. On the global level of the niche that work will probably not be as visible as it used to be, but our analysis provides the lesson that the competition could very well take a different turn in the future.

8. The blow-out of the hydrogen hype

8.1 Introduction[78]

The hydrogen hype in the automotive industry is over so it seems. The industry, governments, and the public have now turned their eyes to the electric car in the hope to find the clean car of the future. In this paper I discuss the general notion of technological hypes and I relate this to the hydrogen hype and the role of the automakers in creating it. I will argue that the automotive industry has contributed to the hype by both developing and showing off their hydrogen prototype cars and by making overly optimistic statements about going commercial with hydrogen. I will contrast this with the current hype-like dynamics for battery electric vehicles.

8.2 Technological hypes

In public discourse, the word hype has a negative connotation and it is often used to talk down short-lived upsurges of attention for some phenomenon and the accompanying unrealistic expectations. When it comes to technology and innovation, experts appear to be fond of using the hype argument: only the enlightened one can separate fact from fiction and thus realistic from unrealistic expectations. Furthermore, to speak of hype is often not just an attempt to make way for realism: it also used to warn for the negative consequences of the hype. That is, hype is said to be followed inevitably by disappointment and that disappointment could put an end to the development of the new technology. Associating hype with just the downside of disappointment does not do justice to the earlier positive effects of the hype however. An innovation may also need a hype to gain legitimacy and credibility in its early stages of development. That is, innovation relies not only on scientific and technological

78 This chapter is published as: Bakker, S. (2010) The car industry and the blow-out of the hydrogen hype, *Energy Policy*, vol.38, no.11, 6540–6544

achievements and breakthroughs, but also on expectations of future potential. More specifically, expectations of technological progress help to stimulate, steer and coordinate collective action on the sides of researchers, engineers, firms and funding agencies in order to make the innovation work. Therefore it is not so much of interest whether expectations are realistic or not, which can only be decided with hindsight, but whether they are widely shared and whether they are powerful enough to create support for the technology in the making. This role, and the deliberate use, of expectations and hype has been analyzed in detail by scholars active in the so-called sociology of expectations (van Lente 1993, Borup et al 2006). Typical hype-disappointment dynamics have been studied in this body of literature as well (Brown and Michael 2003, Ruef and Markard 2010, Konrad 2006). A concept that is often taken as reference by these scholars is the '*Gartner hype cycle*'. It is a tool that is used by the Gartner consultancy firm to position emerging technologies on a timescale and to make recommendations about the timing of strategic investments in the technology. Even though hype cycles take on different shapes and sizes for different technologies, the Gartner cycle provides a clear illustration of the basic dynamics. The graph the company uses plots the attention for (or expectations about) the technology on a timeline. An archetypal illustration of the timeline is presented in Figure 8.1. After a first technology trigger, the visibility increases sharply and makes for hype, up until what is called the peak of inflated expectations. As the peak is reached disappointment gets the upper hand and subsequently the visibility drops rapidly, which then results in the trough of disillusionment. After some time the technology might recover and slowly but surely the visibility increases again (now accompanied by more modest expectations) and the technology might make its way to the market after all.

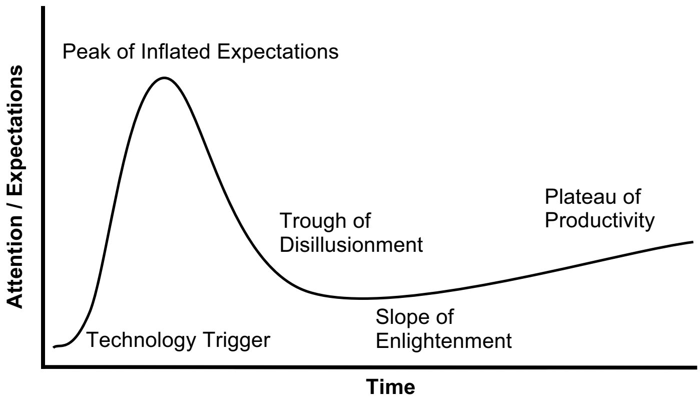

Figure 8.1 The Gartner hype cycle

8.3 Hydrogen and the peak of inflated expectations

In order to understand the role of the established car industry in creating the hydrogen hype, I will first discuss some general understandings of the hydrogen hype. Secondly I will discuss the industry's part in the creation of the hype and the role of their prototypes and statement therein.

Hydrogen has been on the energy agenda for at least four decades. The visions arose for the first time when fuel cells were developed and nuclear energy promised to be an endless, clean and cheap supplier of electricity (Marchetti 1976). The combination of these technologies, linked by hydrogen, was the seed for the vision. The need for an alternative to fossil fuels can be seen as fertilizer. This two-sided development of the vision can be interpreted as a bottom-up move for the application of new technologies (nuclear power and fuel cells) and a top-down move for an energy regime change. Today one can distinguish between three general rationales or '*leitbilder*' for hydrogen visions: sustainability, energy security and decentralization of the energy system (McDowall and Eames 2006). Although not exclusively, the use of hydrogen as energy carrier has been associated strongly with the car industry and the car of the future. Stationary applications, in which hydrogen can serve as an energy storage medium, have also been proposed but these have never dominated the hydrogen debate.

The recent rise and subsequent decline of attention for hydrogen as fuel of the future reflects the basic characteristics of the Gartner hype cycle. At the height of the hype, some experts already made claims about hydrogen being a hype (Romm 2005) and more recently other engineers and scientists have also claimed that the hype is now over (Frenette and Forthoffer 2009).

Even though public funding has not immediately been threatened by the apparent disappointment and decrease of visibility (Ruef and Markard 2010), more recently the US Department of Energy FY2010 funding was cut to a minimum by secretary Chu. It was only because of Congress that the budget was partially restored and further continuation of funding is momentarily highly uncertain (Service 2009). Much of the resources are taken away from hydrogen in favour of the electric car and stationary fuel cell applications such as auxiliary power units (DOE 2009). Whatever the consequences may turn out to be for funding, the notion of hydrogen economy seems to have taken a blow.

As said, the focus of this paper is on the car industry's actions and statements that have driven the hydrogen hype to its peak. Hypes are created in complex social processes and it is impossible and unjust to point at one actor only. One could suspect that the hydrogen hype is the result of over enthusiasm and over promising by the automotive industry, energy suppliers, scientists, and governments together. In this paper, the automotive industry's role in creating the hype is studied. To do so I return to the original description of the hype cycle and especially the peak of inflated expectations. O'leary (O'Leary 2008) quotes the founder of the hype cycle Jackie Fenn on this phase:

> a phase where *"Over-enthusiasm and unrealistic projections, a flurry of well-publicized activity by technology leaders result in some successes, but more failures, as the technology is pushed to its limits. The only companies making money are conference organizers and magazine publishers."* (Fenn 2007)

It is hard to tell whether hydrogen technologies have actually failed and whether this is the consequence of '*pushing the technology to its limits*', but one could safely say that they have not lived up to expectations, for instance in terms of cost reductions and driving range. For instance, the hydrogen car that is closest to market introduction, with small series production of hundreds of vehicles, is the Honda FCX Clarity. The production costs of this vehicle are subject to rumours rather than facts but it most certainly is much more expensive than comparable conventional cars (the price may be up to $ 1 million each) and it only has a maximum range of about 240 miles[79]. Many hydrogen experts, e.g. Joseph Romm (2006), will argue that hydrogen was always overestimated and would never have been able to live up to its inflated expectations. But whether or not expectations where indeed too high is not so much of interest here. Starting from the sociology of expectations, I take a more constructivist position here and ask the question what the sources of the hydrogen hype were and what the exact role of the industry was in creating it.

8.4 Measuring hype

The existing literature on expectations and hypes uses media attention as measure for visibility of the technology and thereby as a yardstick for hype (Ruef and Markard 2010, Geels et al 2007, Alkemade et al. 2006). Media attention is then measured in quantitative terms (counting positive and negative articles) as well as qualitative in order to gauge the hype more accurately. I propose to take a different approach by measuring the industry's prototyping efforts and to analyze the accompanying statements made by the OEMs. The first measure is thus the number of hydrogen prototype models that are constructed and presented by the manufacturers. To study the prototyping activities a database was compiled with prototypes of hydrogen vehicles that were developed from 1960s onwards. The data was collected through an online search process and by comparing and combining a small number of existing databases[80]. The database includes both hydrogen fuel cell and hydrogen combustion engine vehicles.

The second measure for hype builds on statements that were made by the industry spokespersons on their intentions on taking hydrogen cars into production and releasing them on the (consumer) market. To gather the statements, the archives of a leading information source on the car industry[81] were used. To find the relevant statements the following search terms were used: 'hydrogen' and/or 'fuel cell'. The combination of these search terms ensures that both statements about (hydrogen) fuel cell vehicles and hydrogen internal combustion engine (ICE) vehicles are found. This search resulted in 151 unique hits of which 20 contained explicit statements on planned or estimated year of production and market entry.

79 According to Honda, automobiles.honda.com/fcx-clarity/refueling.aspx (visited sept10-2009)

80 www.netinform.net/h2/, www.hydrogencarsnow.com, consulted from May 2008-March 2009

81 www.just-auto.com

Prototyping activities

Prototypes are not only used as R&D tools in a trial and error learning method in which novel technologies are fitted together and tested in the configuration of the prototype, they are also used as communication tools. Manufacturers show off their latest achievements and designs at car shows and in car magazines. By doing so, the prototypes are used as expectations tools, materialized expectations, to shape expectations with consumers, governments, competitors and so forth. The message communicated hereby is twofold. On the one hand prototypes are used to showcase the potential of the novel technologies and to receive feedback from users in the test and demonstration programs that are often set up. On the other hand, manufacturers show the world that they are actually working on the (sustainable) car of the future. Both of these messages are important for the manufacturer since it needs to convince outsiders that it is a) taking its assumed responsibility in producing more environmentally friendly cars and b) that the paths they choose to follow in their search for the car of the future are indeed viable and credible. Hydrogen prototypes have been around for over 40 years, but a peak in prototyping activity started only 15 years ago (see Figure 8.2). The most probable trigger for the peak was the California mandate on zero-emission vehicles (van den Hoed 2005). Patent statistics have shown that car manufacturers performed research on all thinkable alternatives such as biofuels, electric, hybrid, and hydrogen vehicles (Bakker 2010, Oltra and Saint Jean 2009, Pilkington et al 2002, Frenken et al 2004, van den Hoed 2007). However, for the long term, the industry claims that hydrogen and battery-electric vehicles are the most promising alternatives. And from prototyping activities in the industry between 1990 and 2006 it is clear that the hydrogen was the favoured option (Bakker et al. 2009).

During the peak that lasted roughly from 1997 till 2006, 189 prototypes were constructed. All but a few of these were developed by the incumbent industry. BMW, Honda, Ford, Daimler (DaimlerChrysler during most of the time) and Toyota were the industry leaders with respect to hydrogen prototypes. All other major OEMs were also involved in hydrogen prototyping, however to a lesser extent. From 2006 onwards prototyping activities decreased sharply. The exact explanation for the decline of hydrogen remains a matter of controversy. Some experts suggest that a number of the companies prefer to scale up their hydrogen programs in the direction of commercialization and therefore no longer produce prototypes. Honda and Daimler have done so, for instance (Bakker et al. 2009). A more likely explanation however, may be the shift towards hybrids, plug-in hybrids and full battery electric vehicles.

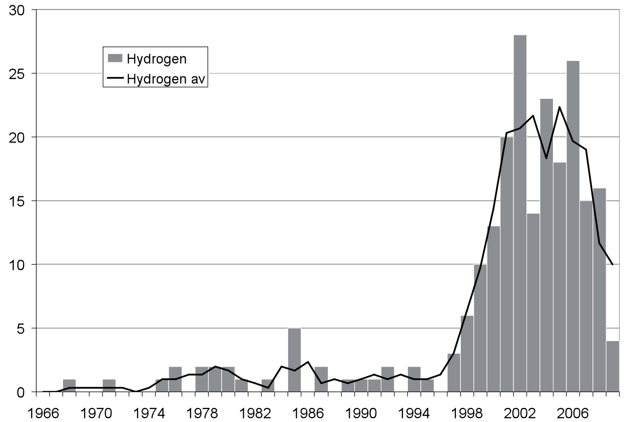

Figure 8.2: Hydrogen prototypes, number of prototype models per year, with three year average line added

Statements

To gain more insight in the rise and fall of the hydrogen hype we have collected statements of car manufacturers in which they have made claims on expected and planned timing for scaling up production and entering the market. It is hard, and most probably not just, to compare all the statements on the basis of the market entry year that was mentioned. There are significant differences between claims such as: start of production, market entry, producing cars that are commercially viable and affordable for consumers, reaching mass market, and significant market shares. However, all of these have in common that they relate to the assumed "readiness" of the technology and the availability of the vehicles on the market.

When we turn to the statements that were put forward by industry spokespersons, often CEO's or heads of R&D departments: we find that Daimler, Honda, Toyota, GM, Ford, and Volkswagen have made explicit comments about the expected market release of hydrogen cars. The statements are listed in Tables 8.1 and 8.2. Especially Daimler, Honda, Toyota and GM have made strong statements, in 2001, about being ready for market in 2004. Daimler claimed furthermore to invest 1 billion dollars in hydrogen technologies. In 2002 however, Ford, GM and Toyota came out with statements that either postponed the planned year of release or at least warned that reasonably priced cars were much further away. In later years only Honda and Daimler issued statements about market entry within a couple of years. The rest of the industry leaders only talked about going commercial after 2010 and beyond.

Table 8.1: Optimistic statements

Year	Firm	Statement	Years ahead
2000	Daimler	2002 busses on market	2
2001	Daimler	FCV's on the market in 2004	3
2001	Honda	FCV's on the market in 2004	3
2001	Toyota	FCV's on the market in 2004	3
2001	GM	FCV's on the market in 2004	3
2001	Toyota	FCHV4 on the market in 2003	2
2002	Ford	Start production 2004, full launch 2010	2
2006	Honda	Sales from 2009	3
2007	Daimler	B-Class production in 2010	3
2008	Daimler	On sale 5-8 years	5-8

Table 8.2: Modest Statements

Year	Firm	Statement	Years ahead
2001	Toyota	Reasonably priced 2010 earliest	9
2002	Ford	2010 50k/yr production	8
2002	GM	End of decade retail market	8
2002	Toyota	10-15 yrs relatively modest price	10-15
2003	Toyota	No significant volume before 2015	12
2003	GM	May put FC's in cars end of decade	7
2003	Ford	Commercial in 2020	17
2004	Ford	If ever…	-
2005	Honda	5% share in 2020	15
2007	VW	Not widely available till 2020, infrastructure	13

A rough divide can be recognized between the most optimistic promises that were made in those early years, when the statements reflected hopes of entering the market in two to three years time, and the more modest statements in the following years. The industry then showed more modesty with claims on market entry in seven to eight years. But some of the optimistic and modest statements are made in the same year and new insights and sheer disappointment in the technology's progress cannot be the only explanation. One possible interpretation, which is somewhat speculative, of this divide is that the industry actually has two repertoires of hydrogen related statements. One repertoire consists of highly optimistic statements about hydrogen and might very well be geared towards raising additional, governmental, funds for R&D and demonstration projects. And furthermore this repertoire is used to highlight the firms' innovativeness and good intentions with regard to developing and commercializing cleaner cars. The other repertoire, with the more modest statements, is possibly used to hold off strict emissions regulations that governments might want to impose in their belief that the technology is 'ready'. It could have been the earlier experience with the zero-emission vehicles mandate in California that has made the industry somewhat cautious to be overly optimistic about the readiness of hydrogen vehicles. Collantes and Sterling (2008) describe in detail how optimistic statements from the automotive industry, most notably from General Motors, had convinced Californian policy makers that the time was right to force the introduction of electric vehicles. In response, the industry started to stress the shortcomings of electric vehicles and the high costs associated with their market introduction and the mandate was withdrawn.

In order to explain why hydrogen cars will take so many years to become feasible, the OEMs provide two main arguments, the first is the cost of the fuel cell system and thus of the hydrogen car as a whole. The second argument builds on the lack of hydrogen infrastructure that is needed for any consumer to even consider buying a hydrogen vehicle. Typical statements are listed in Table 8.3. Of course, the chicken and egg problem is a much debated issue in hydrogen communities and the companies involved. Both sides, the automotive and energy industry, tend to point to each other for taking up the glove and solve this issue. GM for instance, in 2008, asked the energy industry explicitly to build more hydrogen fuelling stations.

Especially the infrastructure issue is somewhat outside the responsibility of the car industry and is therefore well suited to explain the failure of commercialization of hydrogen cars.

Table 8.3: Firms' explanations for hydrogen disappointment

Year	Firm	Statement
2000	Honda	Shift to FC when infrastructure is completed
2000	GM	Cost reductions, safe and reliable infrastructure
2003	Toyota	H2 not be practical until a more efficient method of producing hydrogen without CO2 emissions had been developed
2007	Honda	FC long way from economic, infrastructure issues as well
2007	VW	The problem lies mainly in providing a hydrogen infrastructure
2007	Toyota	Cost of the FC system
2008	Toyota	Cost and infrastructure
2008	GM	Energy industry must build more hydrogen fuelling stations

Since car companies are the most important actors with respect to the commercialization of hydrogen vehicles, it seems logical to assume that their statements had a huge effect on expectations held in general surrounding hydrogen as fuel of the future. Especially statements on market entry find significant resonance in the expectations held by wider society and governments.

Nonetheless, statements where highly promising in 2001 and some remained so up till 2007. Governments and consumers have taken these messages and shaped their expectations of the hydrogen car accordingly. For instance, public funding in Germany for fuel cell and hydrogen technology have risen since the turn of the millennium (Budde and Konrad 2009). And the EU Joint Technology Initiative for hydrogen technologies is focused mainly on demonstration projects and the build up of the hydrogen infrastructure, rather than on additional R&D on propulsion technology. Indicating that governments have taken the message that hydrogen is to be taken serious and that support for the up scaling of hydrogen technologies is timely.

8.5 Conclusions

Contrary to popular belief, hydrogen is not always ten years away: it used to be only two years into the future. With its prototypes and overly optimistic statements, the automotive industry has had a share in creating the hydrogen hype. On the one hand this has led to increasing support from sponsors, as the result of the high expectations. On the other hand it created huge potential for disappointment in governments and the general public. As technological breakthroughs were not realized and market entry was not achieved, the resulting disappointment has led to a breakdown of expectations and paved the road for the hybrid and the return of the electric vehicle. The industry's double repertoire of both highly optimistic and more modest statements, suggests that the statements are used deliberately to serve the industry's interests whenever needed.

Strategic management of expectations (Alkemade et al. 2006) is suggested to balance the positive and negative effects of hype dynamics. It is however questionable whether any actor, or group of actors such as the automakers, is capable of managing the expectations surrounding such highly anticipated technological options. Presenting prototypes and making positive statements is part of the strategic behaviour in the industry in relation to competitors and towards (future) customers. There is an individual incentive for firms to make bold statements about their technological capabilities and good intentions with regard to the environment, but there is only a collective and indirect incentive to remain modest. Further research might shed light on the necessity and feasibility of strategic expectations management.

Today however, the hype seems over and the automotive industry speaks hardly of anything but hybrids and electric vehicles. Funding for hydrogen seemed to remain stable (Ruef and Markard 2010, Suurs et al 2009), but funding in the US is highly uncertain and much of the funding is shifted to electric vehicles. This does not imply that hydrogen vehicles will never be commercialized, but they have taken a blow. For electric vehicles, the same dynamics appear today as in the early years of the hydrogen hype: a multitude of prototypes in combination with highly optimistic statements from the industry on entering production. There is one difference however. In case of EVs there are a far greater number of new-entry firms that have developed and marketed EVs. This is a sharp contrast with the hydrogen prototype hype in which only the incumbent OEMs were involved (Bakker et al. 2009).

Without neglecting the positive outcomes of hype on public and private funding for R&D efforts, more modest promises could serve the development of sustainable mobility better. Be it for the revival of hydrogen or the current surge of battery electric vehicles. For policy makers the challenge is to remain open to different options instead of following hypes as they come and go.

Acknowledgements

I would like to thank Paul Hagen for his empirical contributions and Simona Negro and Roald Suurs for their comments on earlier drafts.

9. Conclusions and reflection

More than a working vehicle or particular design, the hydrogen car is the denominator of a wide range of enabling technologies, designs, prospective sociotechnical systems, and societal visions. In Chapters 2 to 8 it was shown that and how multiple designs and configurations have competed among one another to secure their position in the wider hydrogen vision and the prospective chain of hydrogen technologies. It is also clear that the development of the hydrogen car cannot be understood without taking into account its competitors as well. From the shared notion throughout the car industry, and also within governments and wider society, that today's automobile can and will not last forever, different actors have explored a range of alternatives.

Starting with General Motors' first serious prototype in 1967, most car manufacturers have developed series of prototypes. It was shown in this thesis how these manufacturers have tried and tested a range of design options throughout the years. At the height of the latest hydrogen hype, starting in the second half of the 1990s, when strong pressure was felt to develop commercially viable low and zero-emission vehicles, resources were readily available and many different enabling technologies were being developed simultaneously. The wide variety became apparent in numerous prototypes, patents, and car magazine articles. And it was shown that almost all car manufacturers, and governments alike, maintained portfolios of hydrogen technologies.

A peak in attention for, and expectations of, hydrogen cars appeared around the turn of the millennium. There have been hydrogen peaks before, but this one was the most prominent so far and it is often referred to as a hype. As elaborated in Chapter 7, before and after the latest hydrogen hype, there were periods of high expectations with regard to the battery-electric vehicle. Indeed, hydrogen and battery-electric vehicles can be said to compete and they have, as was shown, alternated in terms of high expectations. In addition, biofuels and natural gas powered cars have also drawn quite some attention in the last 10 to 15 years. In the meantime different types of hybrid electric cars have found their way to the market, but these tend to be seen as transitional and not as the cars of the long-term future.

Competing technologies

The selectors in the car industry as well as in governments have maintained portfolios of options in the form of R&D trajectories in the firms, or publicly funded research programs. They have not limited themselves to one option alone. Even though these actors were able to maintain portfolios of options, they still needed to make choices, as their resources are finite. It was studied how options were included in the portfolios or not. Portfolios widened or narrowed over time in terms of the numbers of options that were being developed. Selection pressures gave rise to a competition between the different options. They competed for R&D funding, both public and private, but also for favourable regulations and the build-up of a supportive infrastructure for instance. In Chapter 1 it was argued how the complexities of the hydrogen vehicle are translated into a prospective chain of technological options. The prospective chain of hydrogen technologies consists of four major components - production, distribution, storage, and conversion – for all of which multiple options are available. And hence, for each component there is a competition of technological options, while on a higher (system-) level, the hydrogen car with all its design options competes with other potential cars of the future.

In Chapter 1 it was also argued that technology selectors, given the emerging and prospective nature of the options, can not assess the different options on the basis of proven performance, as that is still highly uncertain, but rather on the basis of how the options are expected to perform in the future. Likewise, the enactors have to find means to convince the relevant selectors of the potential of their solutions. This gave rise to the central research question of this thesis:

How do emerging technologies compete?

To study the competition between emerging technologies, the quasi-evolutionary model of technological development (van den Belt and Rip 1987, Schot 1992) was used and combined with the literature on technological expectations (van Lente 1993, Borup et al 2006). The variations that compete for selection, it was argued, are put to the fore by technological communities (Rappa and Debackere 1992, Debackere and Rappa 1994, Lynn et al 1998, Rosenkopf and Tushman 1998) of actors that develop those options: the enactors. The members of these communities actively engage in expectations work by convincing others of the potential of their variation. On the selection side, work is needed to assess the expectations and determine which of the variations are indeed promising: the work of selectors. In Chapter 2 the research model was elaborated into a framework of 'arenas of expectations' to investigate and understand the exchange and assessment of technological expectations (Figure 9.1).

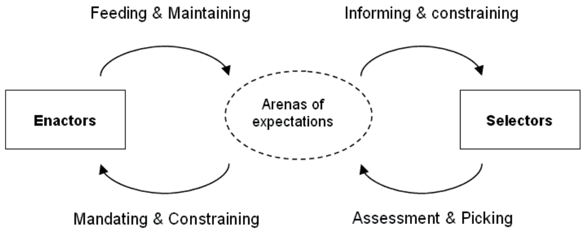

Figure 9.1: Arenas of expectations as linchpin between the enaction and selection of emerging technologies (Bakker et al 2011).

In this concluding chapter, the findings from the individual chapters are brought together according to the elements of the framework: arenas of expectations, the enactors and selectors, and the four arrows that indicate how the enactors and selectors relate to the arenas of expectations.

First, it is discussed why the arenas were introduced and how they are to be understood. And, answering the first sub-question, the distinction between enactors and selectors is clarified and it is argued that these are roles that actors perform rather than fixed positions.

Then, with regard to the second and third sub-question respectively, it is discussed how the enactors have advocated their options and how the selectors have assessed these. The conclusions are drawn for the expectations work of the enactors: how do they feed and maintain expectations towards their audiences? And, how does this result in a mandate and to what extent are the enactors constrained by the outcomes of the expectations battles in the arenas? Then, conclusions are drawn with respect to the selectors and their expectations work: how do they inform themselves, how do they assess the different promises and expectations, and how are they constrained by the outcomes? And, in turn, how do their assessments and technology selection criteria and decisions constrain and enable the competition? As a next step, Section 9.3 details the intimate interrelatedness of enaction and selection. Section 9.4 discusses the contributions of this thesis to the different strands of literature from which this thesis has drawn: the sociology of expectations, innovation studies, and sociotechnical transitions. Section 9.5 offers a reflection on the question to what extent the findings in this thesis can be generalized. Section 9.6 provides suggestions for both enactors and selectors: can expectations be managed and what could this yield?

What are the arenas of expectations?

The notion of arenas of expectations was introduced, by implication, as a concept to investigate and understand the exchange and assessment of technological expectations. With the enactors and selectors placed on opposite sides, arenas form the linchpin between two groups of actors. The concept of arenas refers to the exchange and assessment of expectations, which is not just a bilateral process between one enactor and one selector. As was shown in this thesis, the competition between emerging technologies involves many different actors and a wide variety of earlier exchanges and assessments of technological expectations. That is, expectations resonate with the ones that have been voiced in the past and the extent to which these have come true, as perceived by the relevant actors. To extend the arenas metaphor, the arenas are not cleared of blood after each battle and new battles take place in the dirt of the earlier ones. And as the spectators remain largely the same throughout the years, they will often remember the successful and failed expectations of the past.

In the most basic interpretation the arena is bound in terms of time and space. An arena could then be a series of conferences, a specific scientific journal, a hearing of experts, or board meetings of a car manufacturer. These would then be very much like the bridging events of Garud and Ahlstrom (Garud and Ahlstrom 1997). However, on the basis of the findings in this thesis, it can be argued that a more open interpretation of the arenas does more justice to the dynamics of competing emerging technologies. Such an interpretation defines the arenas as socio-cognitive spheres in which a wide variety of competing expectations is brought together and in which expectations and their assessments from the past and from different sources accumulate. The important point is that 'expectations assessment' does not occur as a singular event, but takes place in arenas where they are judged in terms of their credibility. For instance, to illustrate the cumulative nature of expectations in the arenas, the current disappointment with hydrogen cannot be explained as an outcome of a single assessment somewhere recently. It is the result of accumulated promises and utopian visions on the one hand and an accumulation of failed promises and expectations on the other. Chapter 7 showed how many different actors have added to this and made their assessments in the midst of all circulating promises and expectations.

The arenas of expectations thus contain accumulated expectations, accumulated assessments and the continuous exchange of expectations in various ways. Arenas of expectations thus differ from discourse arenas (Ruef and Markard 2010) to the extent that they include action as well. The construction and demonstration of prototype vehicles, early lease programs, funding schemes, etc.: all these activities should be seen as exchanges of expectations and assessments.

The different chapters in this thesis have described and measured the dynamics of expectations in a number of arenas, by using a set of data sources such as scientific journals, a patent database, car magazines, and prototypes. In table 9.1, four arenas of expectations are listed and it is indicated in what chapters they were studied and what data sources were used. Note the nested hierarchy in which the metal hydrides arena is part of the wider storage arena, which in turn is part of the car of the future arena. Expectations of the hydrogen car that circulate in the 'car of the future' arena are thus, at least partly, accumulations of the credible expectations that have emerged from the component-level arenas.

Table 9.1: The Arenas of Expectations that were studied

Arena	Chapter	Data sources for expectations in and out of arenas
Metal Hydrides	2,3	interviews, journals, foresight reports
Storage	2,3,4,5,6	interviews, journals, foresight reports, prototypes, patents, minutes
Conversion	4	prototypes, manufacturers' statements
Car of the future	7,8	prototypes, manufacturers' statements, car magazine *AutoWeek*

Who are the enactors and selectors?

In innovation, different technological options can be seen as the variations and the selection environment can be found in the market or other institutional structures. In the case of the hydrogen vehicle the market is not truly at work, and to study the pre-market dynamics of variation and selection it was decided to use the notions of enactors and selectors. The enactors are defined as those actors who develop and advocate their technological options, and the selectors are those actors who select one or more options for further support (Garud and Ahlstrom 1997, Rip 2006).

In the cases that were studied in this thesis, the distinction between enactors and selectors was not as straightforward and certainly not as static as it might be taken from the basic research framework of Chapter 1. In Chapters 2 and 6 it became clear that these are not fixed positions of the actors in the innovation process, but that they are roles that actors play in a given innovation context. And, an actor can perform both roles, sequentially or even simultaneously in a hierarchy of technologies and systems. Sequentially, an actor might select a technological option and enact it from that moment onwards. For instance, a car manufacturer may decide to engage in the development of fuel cell technology (selection), and becomes an enactor afterwards when it tries to find support from governments and acceptance by future customers. The same goes for a scientist that enters a research field, say metal hydrides for hydrogen storage: he or she selects that field and becomes an enactor of the same field from there onwards.

An actor who is active at the level of hydrogen systems acts as an enactor of the hydrogen vision as a whole. Simultaneously, this actor is also engaged with the selection of hydrogen technologies. To illustrate, a lead developer of hydrogen cars in an automotive firm enacts the hydrogen vehicle as a whole and at the same time acts as a selector for the most promising storage method to be incorporated in the vehicle.

From innovation literature, the concept of technological communities (Rappa and Debackere 1992, Debackere and Rappa 1994, Lynn et al 1998, Rosenkopf and Tushman 1998) was taken to define and delineate the sets of actors that together enact a specific technological option. In the empirical chapters it was shown, but not always highlighted, that a distinction can be made between actors that are tied to their specific community (monogamous enactors) and actors that move from one community to the other more easily (polygamous enactors). The metal hydrides scientists (in Chapter

2), for instance, were polygamous. They are part of the metal hydrides community and, temporarily, of the hydrogen community as well. But this may very well change when the support for hydrogen is reduced and when another generic promise comes along. In the end, they stress that they are above all (inorganic) materials researchers. In contrast, those actors who have tied their fate much more to the successful enaction of the hydrogen vision cannot jump on another bandwagon as easily. That goes for instance for dedicated hydrogen entrepreneurs in the Department of Energy's advisory committee (Chapter 6), and to some extent for hydrogen engineers in the automotive industry as well. In general, polygamous enactors do not worry so much about the effects of overpromising as they will not suffer as much from any backlash of failed promises. Section 9.6 continous with a discussion of the risks of overpromising, hype and disappointment.

9.1 Enaction

Feeding and maintaining expectations

In Chapter 2 arenas of expectations were presented as the linchpin between the enactors and selectors. And, it was studied how the enactors feed and maintain expectations of their option towards arenas of expectations. The community of enactors performs its expectations work in order to convince their selectors of the viability and potential of its option.
In Chapters 2 and 3 the metal hydrides community featured as the enacting community. As this is by and large a community of scientists, its main outlets are scientific journals, conferences, research proposals, and also meetings with governmental sponsors and other stakeholders. It is through these channels that they are able to explain why metal hydrides could be useful, if not crucial, for the realization of the hydrogen vision. Their arguments are constructs that are built from the actual (current) performance of the metal hydrides, the potential as derived from their theories, and the possibility that a material may be found with yet unknown properties. Their main, and so far winning, argument is not so much that metal hydrides are promising, but rather that its competitors, gaseous and liquid hydrogen storage systems, fundamentally lack any chance of improving significantly due to thermodynamic constraints.

Another group of hydrogen enactors is formed by the car manufacturers that have developed hydrogen prototypes and demonstration vehicles. In their role as enactors of the hydrogen car they have also done their share of feeding and maintaining expectations, as described in Chapters 4, 7, and 8. Interestingly, they have done this not only by means of statements, but also by presenting their prototype vehicles at car shows and in demonstration projects. Here, technological expectations and promises are told through artefacts. Enaction and expectations work, fundamentally, is a matter of storytelling, a discursive activity. Not necessarily with words, but also, as in the case of the hydrogen car, with prototypes and demonstration vehicles. Through the prototypes, the car makers convey messages about the future of hydrogen cars and about the capabilities of the firm to develop such a car and about the good intentions to developing more sustainable cars. One of the messages of the prototypes is also that of progress. Firms, in their statements and presentations, stress the progress that was made in each consecutive prototype model. The most important figure in that respect is the drive range of the cars, but top speeds, increased durability, and size reductions of the drivetrain are also frequently mentioned.

Three general findings with regard to the expectations work of enactors stand out.
First, as shown in the metal hydrides cases, the various acts of feeding and maintaining expectations of an option are not limited to statements about one's own option. It was shown that voicing negative expectations of competing options is just as much part of the process. The metal hydrides community draws on a repertoire of negative claims about other hydrogen storage methods. And along the same lines, the wider hydrogen community is continuously involved in explaining why advanced diesels, biofuels, and battery-electric vehicles hold no real promise on the long run.

Second, in their expectations work, the enactors are very much aware of hype and disappointment dynamics and the risks of overpromising. This is reflected in the interviews with the metal hydrides scientists who need to make claims in research proposals and elsewhere, but who are reluctant to express their claims quantitatively. They stick to the rule that qualitative statements are not as fallible and pose smaller risks in terms of overpromising. The same awareness, albeit too late, was also found in the debates of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) in Chapter 6. Its members acknowledged that hydrogen was overpromised in the past and that hydrogen suffers from that today. Often, some form of 'expectations management' is called for, by scientists as well as the more business oriented members of the hydrogen community. This management should then result in 'realistic' expectations, rather than creating hype that can never be matched by real results.
The car industry seems to have managed expectations of hydrogen in its own way. As polygamous enactors, the car manufacturers are not bound to any of the options and can rather strategically go about raising and lowering expectations of each of the options they have in their portfolio. Highly positive and more modest statements on commercialization of the technology were used deliberately at the same time as was shown in Chapter 8. The goal of this mixed message was probably to gain support for the development of hydrogen vehicles and to avoid all too strict governmental regulations that actually demanded the firms to bring the vehicles to the market. And, strikingly, the car industry has quantified its promises by mentioning the years of commercial introduction of their hydrogen cars.

Third, when disappointment dominates, as was the case in recent years, another form of expectations management by the hydrogen community is invoked to overcome the widespread disappointment. That is, when a technological option is surrounded with disappointment and scepticism, expectations work is intensified and different arguments are offered than before in an attempt to become credible again. The HTAC for instance, felt the need to put more emphasis on current achievements with hydrogen technologies (stressing what is possible today and why this will be even more important in the future) rather than pointing to hoped for technological improvement. Elaborations of possible paths forward to higher performance in faraway futures are then no longer helpful as they are seen to have failed in the past and are no longer credible. An additional strategy is to emphasize the lack of potential of competing solutions even more. To paraphrase: hydrogen might have disappointed, other options are truly futureless.

Mandating and constraining

Enactors do not only feed and maintain arenas expectations, but are also constrained by them. What does an enacting community get back from the arenas? If successful, the community is granted a mandate (i.e. funding and suspension of disbelief) for further work by selectors and with more successful expectations work it may receive a wider mandate. The interviewed metal hydrides researchers felt that they had a wide mandate, in the form of funding, to study and develop a range of alloys for hydrogen storage. Most of them felt no constraints at all and, at least in the Netherlands, a wide variety of materials was studied at the time of the interviews in 2007. Also, Chapter 3 shows the wide variety of materials that were considered. The discovery of favourable characteristics of Li-doped alanates made a range of other materials promising as well. After all, adding catalysts might do for those materials what it had done to the alanates as well.

The HTAC, representing the wider hydrogen community, did feel some constraints when hydrogen was in a phase of disappointment. It felt that the hydrogen mandate was now limited to the most practical, visible, and short-term options. With the hydrogen vision being so much criticised, there was a self-imposed constraint with regard to all too uncertain and long-term R&D.
When looking at the history of hydrogen car developments within the industry, it is clear that within many firms a wide mandate was given to R&D departments. From the second half of the 1990s the portfolios of enabling technologies widen, both in prototypes (Chapter 4) and patents (Chapter 5). Both measures of technological variety hint at a period in which a lot was possible. In later years the variety decreased in the prototypes, and apparently the mandate narrowed. The findings from the prototypes' analysis are not supported by the study of patents however: even though the total number of patents decreased, the variety in the patents continued to grow. Possibly, the manufacturers chose to use only the most practical option in the prototypes and to experiment with other options in the laboratory only.

Differences for system and components

As outlined in the case selection, some cases focus on the component level and others on the system level. This difference is also reflected in the expectations work that is performed. The enaction of components is done at lower levels of aggregation such as specialized journals, conferences and research councils. The enaction at the system level is done towards high level policy makers, CEOs of car companies and to society in general.

The enaction of a component-option seems more straightforward as the object is defined more clearly and the goal is much more specific in terms of relevant performance criteria and the desired levels of performance. On the other hand, as acknowledged by the metal hydrides scientists, there is the risk that such specific promises are easily dismissed as incredible. In the case of carbon nanotubes, such specific performance figures were quickly proven to be wrong and unattainable and this had severe effects on the credibility of that community.

Yet, for the system enactors, the challenge seems more difficult. Even though they will in general not make specific, quantified, promises, they need to communicate a credible vision that relates to a wide variety of issues and future selection criteria. The enacted sociotechnical system with all its complexities and requirements is vulnerable to a host of counterarguments. One way of dealing with such arguments is to distribute the risk: the prospective chain of hydrogen technologies in which a variety of options is presented for each of the elements in the chain. If one option fails to deliver the desired performance, there are always others that might succeed in the future. Yet, such a wide set of options can be interpreted in two ways and the hydrogen community needs to find a balance. One interpretation is that the hydrogen community has a lot of options and that one of those is bound to deliver the desired levels of performance, as is the message in the roadmaps that were introduced in Chapter 1. The other interpretation is that the hydrogen community cannot choose and has failed, after so many years, to develop a single satisfying solution.

9.2 Selection

Informing and constraining

To identify and delineate technology selectors proved to be more difficult as compared to the tracing of enactors. After all, selectors are not connected to a specific technological option or vision but enter the scene because of a particular interest. The selectors are all looking for a solution to their problem, like car manufacturers that, under pressure of anticipated regulation and rising oil prices, explore the options for the car of the future or governments that have reasons to support the development of those vehicles. The case studies show three common strategies of selectors.

First, technology selectors tend to maintain portfolios of options rather than focus on one option alone. The car manufacturers gave their engineers a mandate to develop and test a range of technologies. The portfolios of most firms included both hydrogen and battery-electric vehicles and within those options a multitude of technologies are tried. The same goes for governmental selectors. The DOE Hydrogen Program includes a portfolio of options as well. And, on a systems level, governments tend to support multiple cars of the future simultaneously.

Second, selectors are indeed informed by the arenas of expectations, from which they draw a host of other expectations about the different options as well. Different selectors derive their information from different sources. Within the car industry for instance, the pool of prototype vehicles is a source of information. The prototypes can be regarded as materialized expectations (or as expectations tools) and are thus not only test beds for the engineers, but also communication tools. Hence, the engineers use their own prototypes to enact the hydrogen car towards their management, but also point at prototypes of other firms to underpin the relevance of their work. And, like the prototypes are used to get across a message within the firm, the firm itself uses its prototypes also to voice expectations towards governments, other firms, and wider society.

Third, selectors do not operate as isolated judges, but are just as much informed, and consequently constrained, by the selection decisions of other (competing) selectors. In the analysis of the prototypes, herding behaviour was one of the main explanations for the convergence in hydrogen car designs. Many firms acted as followers and copied the design from a small number of leading firms. And, to be more precise in relation to the constraining effect, a firm that diverges from the emerging dominant design runs the risk of missing out on the benefits that the expected dominant design would profit from: economies of scale and most of all the build-up of a hydrogen refuelling infrastructure.
Likewise, governments are often informed by multi-stakeholder consultations that may take the form of an advisory committee such as the HTAC or the form of a (more or less) formal foresight or roadmapping exercise that are used as inputs for further decision making. Governments also take into account the decisions of other, governmental, selectors. The DOE is an influential selector and, for instance, its storage targets and fuel cell cost targets are often referred to by both enactor and selectors in other arenas as well. And, the other way around, one of the HTAC's most often used arguments was that the US should not fall behind other countries in terms of hydrogen technology development: "the others are moving forward and so should we".

Assessment and picking

In the DOE case study it was shown how these assessments are based on three critical elements. The most basic, but probably the most important element is past progress. An extrapolation of past progress is the basis for technological expectations and past progress seems necessary for credible expectations. Second, additional arguments with regard to a path forward are needed. The past progress cannot simply be extrapolated without underpinning arguments about the theoretical potential of the technological options. Continued engineering can bring actual performance closer to the theoretical maximum and it should be argued what the opportunities are to do so. Third, an option needs to connect to a desirable end-goal. The realization of this end goal should match with the argued path forward as well. Those options that are assessed as credible remain on the research agendas and in the technology portfolios of firms and governments. In the case of hydrogen it was not so much about picking a single winner, but rather about maintaining a portfolio of credible options that are supported simultaneously. Effectively this is a policy of dropping losers, rather than picking winners.

The assessments that are made by selectors are picked up by other selectors and also by the different enactors. Selectors are aware of this and it seems that selection choices are communicated strategically. For instance, the HTAC preferred to communicate the selection of gaseous hydrogen storage in such a manner that it became clear to outsiders that the solution to the hydrogen storage problem was found. Another example is provided by the analysis of prototypes and patents. The publicly visible prototypes reveal different technology portfolios (and selection choices) than the patent data. It seems as if the manufacturers are keen to communicate their optimism towards fuel cells and gaseous storage, but not so much their efforts in developing the on-board reformers. On-board reformers, namely, disturb the zero-emissions ideal that hydrogen and fuel cells derive their legitimation from.

Differences for system and components

How selectors deal with expectations differs for components and systems, and this is very much similar to the differences for the enactors. The selection of systems, in this case the choice between battery-electric and hydrogen cars, relies on expectations of the enabling technologies, the integration of the different components, and also on expectations of other (environment-level) factors. In contrast, the selection of components is much more focused and the selectors' assessment is limited to merely technology-related factors. In the latter case it is more feasible to set targets and end-goals.
Another issue is that, most, selectors are able to maintain portfolios of component options, but can only select one system. Most of all this is a matter of resources, the development of components is less costly than for systems. And, on a speculative note, it could be that the selection of a system is more intricate than the selection of components. BMW selected the hydrogen car because it expected its customers to prefer these over electric vehicles. With all eyes on the system rather than on the components, the selection of a single system might come across as more confident than continuing the development of multiple options.

9.3 Interrelatedness of enaction and selection

Processes of enaction and selection are deeply interrelated due to the collective nature of the circulating expectations. Expectations are collective when many of the actors involved share or acknowledge them. However, such a convergence does not necessarily lead to high expectations and may even inspire disappointment. During hype, many actors relate themselves to the high expectations that circulate, and a convergence of positive expectations takes place. The phase of disappointment is characterised by evenly converged negative expectations.

In the case studies it became clear that the relation between technological convergence (narrower selection) and expectations' convergence can take various forms. Sometimes a narrow selection of technological options results in more positive expectations. The HTAC made this into a deliberate strategy: dropping losers to increase expectations of the hydrogen vision. However, in the chapters that deal with the automotive industry, it was shown that despite the narrowing of designs, the expectations of the hydrogen vehicle turned negative. The apparent favoured design could not reach the desired performance levels. The analysis of hydrogen patents in the industry did reveal a less visible, as compared to the publicly visible prototypes, but ongoing search for the right storage system.

Yet, it can be concluded that under pressure, technology selectors chose to limit the number of options in their portfolio. Not only because of limited resources, but also to communicate that a satisfying solution has been found already. And, keeping alive the long-term options is impossible without stressing the problems with the short-term solutions: the enactors of those options need to stress what is wrong with their short-term competitors.

Clearly, there is a dilemma for selectors of a wide vis-à-vis a narrow portfolio. To justify the selection of a wider range of options, a timeline is often added to the portfolio. It is then argued that there are short-term options (gaseous storage, ICE's, hydrogen production from natural gas) and more long-term options (metal hydrides, FC's, hydrogen from renewable electricity). Such a timeline is supposed to communicate that the prospective chain is close to realization already, by means of the short term options. At the same time it communicates that in the future the problems will eventually be overcome by those rather long-term solutions.

9.4 Contributions to innovation studies

Sociology of expectations

The sociology of expectations, as explained in Chapter 1, deals with the role of technological expectations in innovation processes. Its central claim is that expectations of a prospective technological option can stimulate, steer, and coordinate its further development (Borup et al 2006). In Chapter 1 it was argued that the sociology of expectations has so far concentrated on the role of collective expectations: those expectations that are widely shared, accepted or easily referred to. Such collective expectations can have a structuring role in innovation processes as they enable, but also constrain, the innovating actors. In cases of positive collective expectations, for instance, technology developers may be granted a mandate for further work by their sponsors and managers. In the case of single technological trajectories such conceptualizations of technological expectations adequately explain the relation between expectations and innovation dynamics.

In the case of competing emerging technologies however, such conceptualizations do not suffice. When multiple options, and their developers, compete for (finite) resources (of whatever nature) the question arises which of the options is granted a mandate and why? And, following the proposition of the sociology of expectations, this question can be translated into: how to explain that only some of the options are surrounded with the high expectations and why are these options thought to be the most credible? Whereas the sociology of expectations is mostly concerned with the performative and structuring role of expectations, the question now shifts to: where do those competing expectations come from and how are they assessed in terms of credibility? It was argued in Chapters 1 and 2 that the role of agency is not sufficiently elaborated in the sociology of expectations to come to terms with these issues. That is, expectations are not just out there, but instead, they are actively shaped, negotiated, and maintained by (competing) communities of enactors on the one hand and selectors on the other.

In the technological expectations literature it is acknowledged that expectations are actively shaped and voiced by interested (en-)actors (van Lente 1993, Borup et al 2006, Brown and Michael 2003, Berkhout 2006). But, and this is an addition of this thesis, there are also actors that assess these expectations and either accept or reject them. These selectors need to, as a result of their position or role, distinguish the credible expectations from the incredible and they do so according to varying sets of criteria. From the interplay between the enactors and selectors, credible expectations emerge.

With the explicit introduction of the roles of enactors and selectors into the sociology of expectations and the conceptualization of arenas of expectations as their battlegrounds, the role of agency is stressed. Expectations work is the work of human actors and forceful expectations are the outcomes of the battles and negotiations between enactors and selectors. These expectations are forceful in local practices in which technology selection takes place- say the R&D department of a car manufacturer or the DOE Hydrogen Program - but also at a higher level of aggregation.

A second contribution to the sociology of expectations is the exploration of a number of possibilities to measure expectations. The sociology of expectations is by and large a field of qualitative analyses, and quantifications of expectations are rare. In this thesis, the enactors' expectations have been quantified by means of scientific papers and the argumentation provided in there, and by means of prototype vehicles. The set of prototypes has also been used to quantify the selectors' expectations. That is, the design choices in the prototypes reveal those options that the car manufacturers' deemed most promising at the time of construction. Furthermore, patents have been used to measure the car manufacturers' expectations of the different hydrogen storage options. The fact that these measures have yielded contrasting results (convergence in the prototypes versus divergence in the patents) points to a difference between rather specific expectations for the short-term, as revealed by the prototypes, and more explorative expectations for the long-term, as revealed by the patents. A second distinction can be made between those options in the portfolio that are shown to the outside world actively through prototypes, and those that remain somewhat more hidden in the form of patents

Levels of Expectations

A third contribution relates to the interdependencies of levels of expectations. As discussed in Chapter 1, different typologies of expectations have been suggested in the literature. Van Lente distinguished between specific, functional, and scenario-like expectations (van Lente 1993). These proved useful for the analysis, or dissection, of expectations of a single technological option: its levels of performance, its functionality, and its future sociotechnical context. In this thesis, another typology was proposed and used to address the situation of competing options. A distinction is made between expectations of future sociotechnical environments, systems and components. Such a typology follows the (prospective) nested hierarchy in which the different hydrogen technologies are enacted and selected (Figure 9.2). The prospective system, the chain of production, distribution, storage, and conversion is thus an example of a prospective structure that can be filled in with different technological options (van Lente and Rip 1998a). That system needs promising components, and the other way round, the components need a promising system.

The hydrogen car is to be located at the system level in this typology, as a configuration of two component technologies from the prospective chain: storage and conversion.

This thesis focused on competing expectations at the component and the system level. Expectations of future (selection) environments are by and large the same for all competing technologies in this case. The expected shortages of oil, the associated geo-political tensions, worries of climate change, and expected governmental regulations are, roughly speaking, equal to all cars of the future. And, for the enactors of the cars and their components, these expectations are rather uncontested. The challenge for the competing systems is to link up with these expected changes in the environment, and components link up, in turn, with the projected systems. The distinction between systems and components proved useful for the analysis of expectations work in the case of competing options. Essential here is that expectations of component technologies can only be performative if they connect with expectations at the system, and ultimately, the environment level.

These levels should not to be confused with the three levels of the multi-level perspective as the multi-level perspective refers to *old vs. new* competition and the three levels of expectations presented here refer to *new vs. new* competition.

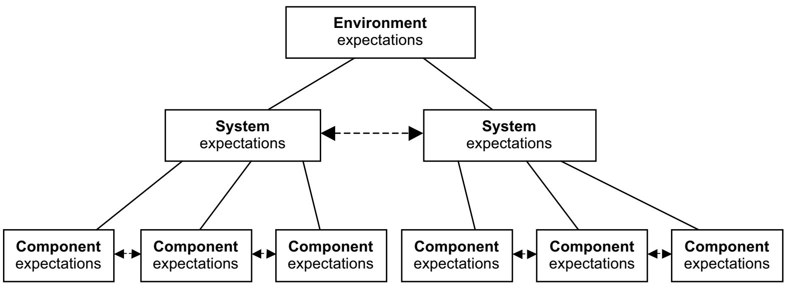

Figure 9.2: Levels of expectations

Credible Expectations

The last contribution to the sociology of expectations relates to attempts to assess expectations. Chapter 6 introduced the term 'credible expectations' and studied what makes an expectation credible to enactors and selectors. Figure 9.3 summarizes the findings. The ingredients of a credible expectation include proven (recent) past progress that can be extrapolated into the future. Furthermore, beyond a basic extrapolation, some argumentation is needed to explain why further progress is possible: the path forward. And, the path forward should get the technological option to a level of performance, in time, that meets some agreed-upon performance level.

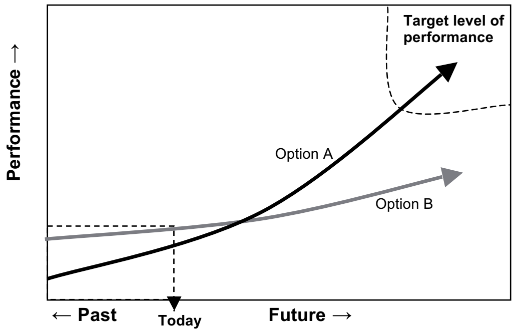

Figure 9.3 The ingredients for the construction of a credible expectation of technological progress

In such constructions of credible expectations, a number of contrasting pairs of expectations can be recognized as are arguments that enactors tend to use in their expectations work. The pairs are listed in table 9.2 and could be of use to selectors when they need to assess the different expectations that are directed towards them (Section 9.6 provides a discussion on this). As depicted in Figure 9.3, when two options compete, the challenge for the enactors of the lower-performing option is to communicate not only why their own option will make progress, but also why the other will not. Enactors can extrapolate their progress, and argue why that is justified based on engineering potential for instance, but also speculate on possible findings in the future. To some options, a focus on the short term is more appropriate, whereas for other options their long-term potential is more appealing. The relevant criteria to judge alternative (the Y axis in Figure 9.3) are often subject to debate as no one can know for sure which criteria will be decisive in the future. Because different technological options 'fit better' with different selection criteria, enactors will argue that 'their' selection criteria will be decisive. So, competing expectations entail a competition of criteria as well.

And finally, there is a distinction between expectations work when collective expectations are very positive and expectations work when they are not. It is needless to say that in the former case expectations work is easier and the type of arguments tend to change as well. In good times, the expectations work is mostly about seizing opportunities, while in bad times, the expectations work is more about stressing the risk of dropping something that eventually may deliver on its promise.

Table 9.2 Contrasting pairs of types of expectations and some fictional examples of statements.

Positive expectations (about own option) "fuel cells costs will go down"	**Negative** expectations (about competing option) "ICE's will always be inefficient"
Extrapolation of the known "fuel cell costs will continue to go down"	**Speculation** about the unknown "we might find new nano-materials that can store even more hydrogen"
Short term expectations of the well known and possibly satisfying option "700 bar are good enough for now"	**Long term** of the highly uncertain but all encompassing option "eventually metal hydrides will provide a optimal solution"
Expected **performance** on a criterion (on a specific criterion) "high pressure storage tanks can facilitate a 500 km drive range"	Expected relevant **criteria** (to match with qualities) "safety will be more important than range"
Offensive strategy during phase of high expectations "everybody agrees that the hydrogen car is the car of the future"	**Defensive** strategy during phase of disappointment "it would be short-sighted to drop the hydrogen car now"

Competing technologies

This thesis also has lessons for the issue of competing technologies. In innovation studies, many different strands of literature address the competition between different technologies or technological designs. In this thesis a number of these were used and some additions were formulated with regard to the dynamics of pre-market competition.

First, the quasi-evolutionary model aims to incorporate pre-market dynamics into evolutionary economists' models of innovation by stressing the anticipation on the supply side: technology developers do not develop technological variations without some understanding of future markets. The framework of arenas of expectations goes one step further. In arenas of expectations, true competition takes place between multiple options and there is not only anticipation on the side of the enactors, but also actual selection by the selectors.

Along the same lines, the idea of pre-market competition was added to the Abernathy and Utterback phased model of the innovation process and to the theory on dominant designs and their emergence. Dominant design theory seems to be dominated by simplistic conceptualizations of competing technologies, thereby ignoring the multitude of selection criteria and, even more so, the very fact that selection decisions are also made well before anyone can know with certainty which option will be superior. In the absence of market forces, it is a combination of current and expected technological performance characteristics, anticipated regulations and strategic manoeuvring of the firms that guides the selection of the emerging dominant design. These technological and strategic factors co-evolve and reinforce each other in two ways. First of all, there is an incentive, due to network externalities and economies of scale, to agree on the best design before market entry. The (technologically) best performing design can only succeed when the majority of firms adopt it. Second, firms that are most active in the development of the emerging technology will give the strongest signals about their expectations of their designs. For other firms, the followers, this is reason to adopt those promising designs as well. These followers do not explore the full variety of design options, but in order not to miss out, they develop a small number of designs in the path that is surrounded by collectively held positive expectations. Their conformity, or herding behaviour, amplifies the expectations held on a certain configuration.

Chapter 5 put to the difference between patents and prototypes as indicators of exploration strategies withing firms: prototypes suggested an industry-wide convergence towards a winning design for the hydrogen vehicle, while the patents showed ongoing divergence. A satisfactory explanation for the difference could not be given. But, while patents are used as indicators of exploration and variety in technology portfolios, this thesis suggests that prototypes might be good , if not better, indicators as well. The patents fail to show those design options that are developed outside of the firms of interest. And, they often deal with single enabling (component) technologies only and are therefore poor indicators of the configurations of components that may be actually of interest to the innovation researcher.

Nonetheless, an analysis of prototypes only is limited as well. For instance, the patents did show that car manufacturers continued to explore some technological options that were no longer showcased in the prototypes. Especially as these were options that are thought to be less desirable, in this case the on-board reformers, for any onlooker it is worthwhile not to take the prototypes, nor the patents, at face value.

Sociotechnical transitions

Finally, this thesis relates to the growing attention for encompaasing, sociotechnical transitions. In Chapters 6 and 7 it was argued that the literature on sociotechnical transitions lacks an understanding of the interactions between different transition paths. (Markard and Truffer 2008, Smith et al 2010, Schot and Geels 2008). Without claiming to have studied these interactions in full detail, it was shown in this thesis that, and partly how, such transition pathways indeed compete with each other in the case of hydrogen vs. battery-electric vehicles. Both options share the same niche, of the 'car of the future' but apparently only one is dominant in the niche at any point in time. This is surprising as most actors and organizations that have helped to create the protected space for the car of the future are rather agnostic to the outcome of the competition. Most car manufactures have worked on both options and governments impose regulations that favour zero- or low emission vehicles rather than one of the options specifically. But still, these actors need to divide their resources between the two options. The competition for funding and the shifts in attention and expectations apparently had an impact on the development trajectories of both options. After the first peak of activity with electric vehicles, much of the funding was taken away from that option by both firms and governments and efforts were put on a hold. Later, when the fortunes for hydrogen car faded, electric vehicles gained a renewed interst. Chapter 6 shows that the perceived failure of, or disappointment with, one option opens a window of opportunity for the other.

In contradiction to a central assumption in the literature on sociotechnical transitions, Chapter 6 also shows that converging design rules do not necessarily lead to high and positive expectations. Yes, the convergence of design rules within a transition path tends to strengthen its story and makes it easier to convince selectors. And diverging designs make for a fuzzy and less convincing story. However, it was also found that, in the case of hydrogen vehicles, the design that the industry had converged to, was not good enough in terms of performance and pricing. The resulting story was no longer convincing and the expectations diverged. Hence, agreement on what works best does not necessarily result in collective positive expectations.

9.5 Reflections on hydrogen as a case study

The findings and conclusions in this thesis are based on case studies of the development of the hydrogen car. The extent to which these findings can actually be generalized is, however, not automatically clear: is the innovation trajectory of the hydrogen car an extraordinary case with unique dynamics? In the following it will be argued that the hydrogen car case study has generated general insights about the pre-market phase of emerging technologies. Furthermore, it can be expected that the findings fit best, but not exclusively, with systemic, eco-innovations.

First and foremost, the findings in this thesis relate to emerging technologies and their competition in the pre-market phase. It is safe to say that hydrogen technologies are emerging technologies. The hydrogen car has been under construction for over forty years without significant market entry. Some of the individual component technologies that are used in hydrogen cars are commercially available, but the hydrogen car is certainly not. The forty years of emergence make hydrogen somewhat different from other emerging technologies. Often, the market is entered at an earlier stage. And while these technologies (e.g. wind turbines or solar panels) are continuously being developed, much of the selection between different designs can then take place in the market and according to market criteria. Those technologies were at some point emerging as well and, without doubt, some selection has taken place in the pre-market phase as well. It is this pre-market phase that is studied in this thesis and to which the findings apply.

In the following, four characteristics of the hydrogen car and its innovation trajectory are discussed to determine to what extent it is indeed an extraordinary case and what limitations apply to the findings. First, a good starting point to answer these questions is the rise of the passenger car in the early 1900s. In those days, multiple designs with combustion and electric engines were in competition (Mom 2004). And even though it was a small market, at least they were competing on a market and consumers actually acted as the selectors. Besides competing with each other, combustion and electric cars were also battling the old regime of personal transport. In those days the sociotechnical regime consisted of trams and horse-drawn carriages. The electric passenger cars that challenged this regime performed probably worse than today's hydrogen cars, but in comparison to the old regime they presented completely new possibilities and levels of performance. Today, the hydrogen car challenges a sociotechnical regime that has engraved itself into society and economy for over a hundred years. It is therefore difficult for the hydrogen car to enter and survive this harsh selection environment and it is not developed to such a level that this is possible yet.

The hydrogen car cannot easily occupy small niche markets. It is after all part of a wider prospective sociotechnical system and the production of hydrogen and the refuelling infrastructure both require sizeable market shares to be economically viable. Thus, the hydrogen car is a case of an emerging technology that faces an existing sociotechnical regime and this is therefore no wonder that it has such a long period of emergence.

Second, the hydrogen car is, and always has been, a product of the incumbent car industry. In contrast, the battery-electric car was also developed by new-entry firms. New-entry firms have strong incentives to enter the market with their new designs, but the incumbents lack such motivations. Without claiming that the car industry has deliberately held off the hydrogen car, it is safe to argue that it has not pushed it onto the market either. Car makers did develop the cars and the enabling technologies, but they have always done so with relatively little risk: they have taken advantage of governmental support for R&D efforts and no firm has decided to start commercial production. As for the electric car, the new-entry firms that developed these have also never been able to gain serious market shares. Today's Tesla's and Th!nk's are available on the market, but with hundreds rather than thousands.

The apparent lack of commitment in the industry with regard to the hydrogen car, makes that onlookers have become rather sceptical and that hydrogen is subject of debate and contestation. As a consequence, attention and positive expectations of hydrogen technologies come and go in waves of hypes and disappointments. These ups and downs of hydrogen expectations, at the system level, are perhaps unique to hydrogen. While the competition between multiple designs and component options has occurred for a prolonged period, there is no reason to assume that such a competition is unique to the hydrogen car.

Third, the hydrogen car is a configuration of components that are being developed and it is, or is supposed to be, embedded in a wider system of supportive technologies. So, multiple designs can compete among one another and expectations at different levels are strongly interconnected. Toothbrush-like, single artefact, innovation is probably less complex to develop and to enact and select. The selection criteria for such innovations are much less contested and the expectations work is limited to that one artefact instead of a prospective chain of emerging technologies.

And fourth, like other eco-innovations, hydrogen is, today at least, an option that is not necessarily 'good' in terms of standard (market-based) selection criteria of price and performance. In general, eco-innovations score high on performance criteria that are normally not those of the market (Faber and Frenken 2009). Regular market incentives are thus lacking for firms to develop eco-innovations, including the hydrogen car. It is only because of anticipated governmental regulations and possible changes in market forces ("in case we run out of oil") that the hydrogen car is developed at all. In other words, the hydrogen car is not so much developed for today's or tomorrow's markets and consumers, but rather for markets and consumers decades ahead. This introduces an extra source of uncertainty, and thus of required additional expectations work, as compared to non-eco-innovations that are geared towards (better) known markets. That is, the end-goals and performance targets are more uncertain for eco-innovations than for regular innovations. To the findings in this thesis this implies that the competition of expectations is more important for eco-innovations than they are for 'market-driven' innovations. In particular, one could argue that the role of environment-level expectations is more important in cases of eco-innovations. This results in a slightly different message in the expectations work for eco-innovations: it is more about the necessity of the solutions and less about the opportunities.

One suggestion for further research would be to study the competition between multiple sociotechnical trajectories or transition paths in more detail. As was argued in Chapter 7, the literature on sociotechnical (sustainability) transitions has so far dealt with single technology trajectories: why these were successful or not. Chapter 7 has shown that the hydrogen and battery-electric vehicles have strongly interrelated dynamics of expectations and that they are in fact competing with each other. The same types of competition can be expected to take place between the different renewable energy technologies. The framework and findings of this thesis may provide a starting point. For example, the conceptualization of technological niches as protection environments that can include multiple technological options opens the possibility of studying the processes that leads to the allocation of protection (resources and institutions) to either the one or the other option.

9.6 Suggestions for enactors and selectors

One of the ambitions of the research project was to learn more about hype and disappointment dynamics and to derive a strategy for better expectations management. It was assumed that waves of expectations with high ups and low downs are eventually detrimental to the innovation process and bring about unnecessary societal costs.
The effects of hype are found first and foremost in easily acquired funding for the enactors. During the phase of hype, less expectations work is needed and it will result in larger and wider mandates. Also, more actors will join the 'bandwagon' and the innovation trajectory is more likely to succeed. The disadvantages during the phase of disappointment are, reciprocally, the withdrawal of enactors and funding, up to the point that developments come to a standstill. In terms of funding, it was thus assumed at the start of this project that the amount of funds that is granted during the phase of hype is far higher than during the phase of disappointment and that the total sum of the funds is eventually lower than it would have been without the overshoot. In comparison to the hype cycle, the 'ideal'

the expectations curve, in the case of successful expectations management, would be a rather straight ascending line or a flat line at a moderate level of attention or expectations (Figure 9.4).
However, not much evidence was found during this project that hype-disappointment dynamics are truly detrimental. Hydrogen has seen a number of hypes and subsequent disappointments and the current situation is not favourable for the hydrogen community. But, the community has already profited a lot from the hype and it is difficult to tell whether it would have been better for the technology's development if the expectations dynamics would have been less dramatic. Even more so, it is questionable whether such expectations management is possible at all.

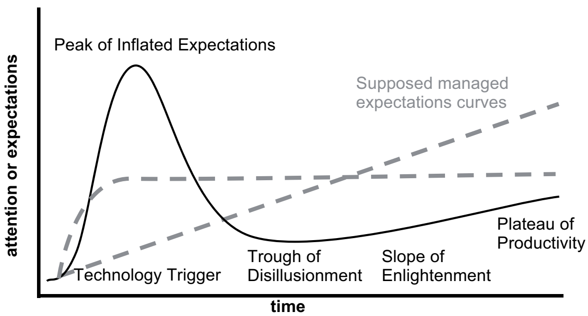

Figure 9.4 Supposed expectations curves in the case of optimal 'expectations management'

A serious risk though, is that funding and developments come to a full stop and much of the gained knowledge is lost. It seems that the current situation with hydrogen is not that grave. Many car companies are still continuing their hydrogen efforts and it is not likely that all knowledge is lost. Also, much of the governments' funding is continued. In Chapter 7 it was questioned whether this is the result of deliberate action or just because policy making is too slow to keep up with the hypes and disappointments. In any case, many projects are continued or even set up newly such as the German plans for a refuelling infrastructure[82]. For smaller dedicated firms that rely fully on the, commercial, success of hydrogen or fuel cells, the situation is probably different and more problematic. Venture capital is nearly impossible to acquire (as was discussed during the HTAC meetings, Chapter 6) and it will take longer for any serious market for hydrogen technologies to take off, if ever.

During the current situation in which hydrogen finds itself in a phase of disappointment, actors, in hindsight, call for a different kind of expectations management. The hype should have been avoided and more 'realistic' expectations should have been voiced, according to them. As other studies have shown, all sorts of actors know how to take advantage of hypes (Konrad et al. 2009, Wüstenhagen et al. 2009). Indeed, in Chapter 8 it was argued that the car industry has indeed used a double repertoire about hydrogen in order to manage the expectations of governments. So again, assuming that hype

82 Joint Press Release on 09-10-2009 by Linde, Daimler, EnBW, NOW, OMV, Shell, Total and Vattenfall: Initiative "H2 Mobility" - Major companies sign up to hydrogen infrastructure built-up plan in Germany

and disappointments are detrimental, especially, for dedicated firms and small projects, would it be possible to manage expectations in such a way that all too high ups and all too low downs are avoided?

The enactor's dilemma: to hype or not to hype?

In Chapter 8 it was doubted whether expectations management is indeed possible. After all, the engineers and other members of the respective technological communities need to communicate to their sponsors why their option is promising and why support is thus legitimized. For them there is hardly any incentive to be modest as they need all the support they can acquire and this is done best with high expectations and bold promises. The risk of overpromising and the subsequent backlash of disappointment are necessarily taken for granted. In other words, for individual enactors there is a strong incentive to voice high expectations of their own technological option as this will provide them with the desired resources. The incentive to remain modest and to avoid hype is collective and is only rewarding in the long run: the community as a whole is ultimately affected by the disappointment and not only the individual enactor. This condition shows similarities with the multi-player prisoner's dilemma or the similar 'tragedy of the commons'. The outcome of the individual's decision is dependent upon the decision of the other(s). And cooperation, by being modest, presents less direct benefits for the individual agent. A hypothetical matrix of the enactor's dilemma is depicted in Table 9.3.

Table 9.3: Hypothetical table of the enactor's dilemma of raising expectations and avoiding hype

The enactors' dilemma	Modest enactor	Hyping enactor
The community is modest	Low reward for all in the community (and steady)	Low reward, but more than competitors in the community (and steady)
The community is hyping	High reward, but less than competitors (short period only)	High reward for all in the community (short-period only)

Even more so, different actors with diverging interests are involved in the expectations work of the community. Some of those have an interest in the final outcome of the innovation trajectory and their ambition is to commercialize and deploy hydrogen vehicles onto the road in large numbers. These actors actually have the collective incentive to avoid overpromising and hype, in order not to jeopardize the innovation trajectory. Others however have only short term interests. The venture capitalist, for instance, who has invested in a start-up company, has every reason to create hype as this will generate a high return on his investment. The venture capitalist's consideration does not include the negative results of eventual disappointment: the consideration is about 'stepping out' before disappointment sets in.

From the perspective of a technological community that competes with another community, say the hydrogen versus the battery-electric community, expectations are even more difficult to manage. At any point in time, one can assume, for the sake of the argument, that a fixed budget is available for both options together, making it a zero-sum game. At that point in time, regardless of the long-term effects, both communities will try to maximize their share of the fixed 'pie'. And consequently, being modest is then not an option. Also, the community that is granted the largest share of the budget is likely to increase the performance of its option through R&D. They thus have the opportunity to make their option even more credible in further selection decisions. Modesty is thus even more unlikely to pay off at the long run in the case of competing technologies: too much is already lost in the first place. The HTAC's deliberations were, from the moment that battery-electric vehicles started 'chipping away funds' from the hydrogen car, aimed at 'enlarging the pie' rather than securing the largest piece of the pie. In the formal wording of the prisoner's dilemma, they tried to turn the affairs into a non zero-sum game in which the total sum of available funding would increase.

The selector's dilemma: to select or not to select

The selectors also have an interest in less dramatic dynamics of expectations. And as it is not likely that enactors are able or willing to manage expectations successfully, it is also, and perhaps even more so, a task of the technology selectors to manage expectations and selection strategies.

In the first place it would be advisable for technology selectors to refrain, as much as possible, from choosing sides at all. And second, if selection is unavoidable, it would be advisable to refrain from choosing sides all too hastily and drastically. That is, selectors should be aware of the ongoing expectations game and be careful not to react immediately to any hype as it comes by. Likewise, in the case of disappointment, they should avoid dropping the disappointing option immediately and completely.

Indeed, hydrogen funding has been relatively stable as compared to the high amplitudes in the various expectations curves that were measured in this thesis. The DOE funding was restored to more or less regular levels and the EU Hydrogen JTI guarantees the continuation of hydrogen projects in Europe. In the US the budget was restored by the Congress even though the DOE's leadership had labelled hydrogen as a disappointing and futureless option. The EU JTI was initiated during times of great expectations and was continued even when disappointments appeared.

These selectors have thus not reacted directly and drastically to hypes and disappointments. This holds no guarantees for the future and, for instance, the HTAC members were not convinced of future continuations of the budget. So, the question remains: should selectors manage expectations more deliberately and how can they do so?

Not selecting at all is the most obvious solution to avoid the pitfalls of hype dynamics. Technology-agnostic policies are one way of triggering innovation without selecting winners or dropping losers. The Californian zero-emission vehicles mandate was technology-agnostic, and so is the EU regulation on fleet-average emission standards. Such regulations trigger demand for zero- or low-emission vehicles and force automakers to innovate without selecting a certain option. Governments can choose to compliment such regulations with R&D subsidies that are equally technology-agnostic. The FreedomCAR project, in contrast, which was solely meant for hydrogen vehicles, would not fit such a strategy. And, for instance, the EU could have chosen to set up a car-of-the-future-JTI, rather than a hydrogen-JTI. The problem of picking and dropping is then not removed completely, but shifted from policy makers to car manufacturers in this case. These are now required to make the selection decisions and these decisions may also be affected by the hype and disappointment dynamics. On an even more speculative note, one could assume that within firms the enactors and selectors (say the fuel cell developer and the CTO) are closer to one another and that knowledge is more equally spread throughout the organization, as compared to firm-government selection decisions. In such cases expectations are assessed more thoroughly and more regularly, and, therefore, less prone to inflation.

Another option to manage expectations is to introduce more explicit accountability in the expectations game. The EU Hydrogen JTI is a 50/50 match of public and private funding and the firms and organizations that profit from the JTI funds need to invest themselves as well. To some extent at least, this makes the expectations game between enactors and selectors more balanced as they then co-select.

The selection problem remains with regard to start-up firms and other dedicated hydrogen developers. After the hype, these actors rely on government support to continue the development of their products. Private investors are not willing to support them any longer and their products are not yet commercially viable. For governmental selectors, policy makers, the question thus remains whether they should continue the support while the private investors are already out and while selectors may have lost their faith in hydrogen as well. The dilemma then is to either end the support (thereby effectively losing the previous investments) or to continue the support with the risk of losing even more on the long run. This is a classic in technology management and innovation policy, and not a topic of this thesis.

However, this thesis suggest that when governments do select 'winners' and the winning options receive funding, it would be wise to evaluate the results over relevant, and in practice most often longer, time spans. While continuous evaluation is a necessity to keep developments on the 'right' track, ex-post evaluations, in which the outcomes are assessed in relation to the initial expectations, should only be executed when one can actually expect some positive results. It would thus be wise to stretch the evaluation timeframes to such an extent that initial expectations are not too hastily turned into disappointments.

This also applies for the current situation. The hydrogen car has gone through phases of hype and disappointment more than once and even though some have declared the hydrogen car dead for now, to discard it altogether would be an undervaluation of the resilience of the wider hydrogen vision and its enactors.

References

Abernathy, W.J. & Utterback, J.M. (1978) Patterns of Industrial Innovation, *Technology Review,* vol.50, 41-47

Agnolucci, P. & McDowall, W. (2007) Technological change in niches: auxiliary power units and the hydrogen economy, *Technological Forecasting and Social Change,* vol.74, no.8, 1394-1410

Alkemade, F., Hekkert, M. & Suurs, R. (2006) Strategic expectations management for emergent sustainable technologies, *DRUID Summer conference on knowledge, innovation, and competitiveness: dynamics of firms, regions and institutions, Copenhagen, CBS, Denmark, June*, pp. 18

Alkemade, F., Frenken, K., Hekkert, M.P. & Schwoon, M. (2009) A complex systems methodology to transition management, *Journal of Evolutionary Economics,* vol.19, no.4, 527-543

Alvarez, R. (2009) Is the Energy Department ready to reboot the country? *Bulletin of the Atomic Scientists,* no.27 March,

Anderson, P. & Tushman, M.L. (1990) Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change, *Administrative Science Quarterly,* vol.35, no.4,

Archibugi, D. & Planta, M. (1996) Measuring technological change through patents and innovation surveys, *Technovation,* vol.16, no.9, 451-519

Arthur, W.B. (1989) Competing technologies, increasing returns, and lock-in by historical events, *Economic Journal,* vol.99, no.394, 116-131

Bakker, S., van Lente, H. & Meeus, M. (2011) Arenas of Expectations for Hydrogen Technologies, *Technological Forecasting & Social Change,* vol.78, no.1, 152-162,

Bakker, S., van Lente, H. & Meeus, M. (2010) The Emergence of a Dominant Design in the Prototyping Phase–An Analysis of Hydrogen Car Prototypes, *Druid Summer Conference 2010*

Bakker, S. (2010) Hydrogen patent portfolios in the automotive industry - The search for promising storage methods, *International Journal of Hydrogen Energy,* vol.35, no.13, 6784-6793

Bakker, S., van Lente, H. & Meeus, M. (2009) *The Emergence of a Dominant Design - a study on hydrogen prototypes; Innovation Studies Utrecht (ISU) Working Paper Series*

Berkhout, F. (2006) Normative expectations in systems innovation, *Technology Analysis & Strategic Management,* vol.18, no.3, 299-311

Bijker, W.E. (2010) How is technology made? That is the question! *Cambridge Journal of Economics,* vol.34, no.1, 63-76

Bijker, W.E. (1995) *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change,* MIT Press, Cambridge

Bogdanovic, B. & Schwickardi, M. (1997) Ti-doped alkali metal aluminium hydrides as potential novel reversible hydrogen storage materials, *Journal of Alloys and Compounds,* vol.253, 1-9

Borup, M., Brown, N., Konrad, K. & van Lente, H. (2006) The sociology of expectations in science and technology, *Technology Analysis & Strategic Management,* vol.18, no.3-4, 285-298

Bowman, E.H. & Hurry, D. (1993) Strategy through the options lens: An integrated view for resource investments and the incremental-choice process, *Academy of mangement review.18.4.,* vol.760, 782

Brown, N., Rappert, B. & Webster, A. (2000) *Contested futures. A sociology of prospective technoscience,* Ashgate, London

Brown, N. & Michael, M. (2003) A Sociology of Expectations: Retrospecting Prospects and Prospecting Retrospects, *Technology Analysis & Strategic Management,* vol.15, no.1, 3-18

Buchner, H. (1980) Perspectives for metal hydride technology, *Progress in Energy and Combustion Science,* vol.6, no.4, 331-346

Budde, B. & Konrad, K. (2009) Interrelated visions and expectations on fuel cells as a source of dynamics for sustainable transition processes, *KSI conference*Amsterdam

Bullis, K. (2009) Q & A: Steven Chu, *Technology review,* no.May 14,

Bush, G.W. (2003) *State of the Union Address, January 28, 2003*

Callon, M. (1980) The state and technical innovation: a case study of the electrical vehicle in France, *Research Policy,* vol.9, no.4, 358-376

CARB (2008) *ZEV Program Fact Sheet,* California Air Resources Board,

Chandra, D., Reilly, J.J. & Chellappa, R. (2006) Metal hydrides for vehicular applications: The state of the art, *JOM Journal of the Minerals, Metals and Materials Society,* vol.58, no.2, 26-32

Christensen, C.M., Suarez, F.F. & Utterback, J.M. (1998) Strategies for survival in fast-changing industries, *Management Science,* 207-220

Christensen, C.M. & Rosenbloom, R.S. (1995) Explaining the Attackers Advantage - Technological Paradigms, Organizational Dynamics, and the Value Network, *Research Policy,* vol.24, no.2, 233-257

Clark, K.B., Chew, W.B., Fujimoto, T., Meyer, J. & Scherer, F.M. (1987) Product development in the world auto industry, *Brookings Papers on Economic Activity,* 729-781

Collantes, G. & Sperling, D. (2008) The origin of California's zero emission vehicle mandate, *Transportation Research Part A,* vol.42, no.10, 1302-1313

Cooper, R., Edgett, S. & Kleinschmidt, E. (2001) Portfolio management for new product development: results of an industry practices study, *R&D Management,* vol.31, no.4, 361-380

Cusumano, M.A., Mylonadis, Y. & Rosenbloom, R.S. (1992) Strategic maneuvering and mass-market dynamics: The triumph of VHS over Beta, *The Business History Review,* 51-94

Cyert, R.M., Dill, W.R. & March, J.G. (1958) The role of expectations in business decision making, *Administrative Science Quarterly,* 307-340

Dagani, R. (2002) Tempest in a tiny tube, *Chemical & engineering news,* vol.80, no.2, 25-28

Danholt, P. (2005) Prototypes as performative, ACM New York, NY, USA , pp. 1-8

Das, L.M. (1996) On-board hydrogen storage systems for automotive application, *International Journal of Hydrogen Energy,* vol.21, no.9, 789-800

Das, S.S. & Van de Ven, A.H. (2000) Competing with new product technologies: A process model of strategy, *Management Science,* vol.46, no.10, 1300-1316

David, P.A. (1985) Clio and the Economics of QWERTY, *The American Economic Review,* vol.75, no.2, 332-337

de la Casa-Lillo, M.A., Lamari-Darkrim, F., Cazorla-Amoros, D. & Linares-Solano, A. (2002) Hydrogen Storage in Activated Carbons and Activated Carbon Fibers, *Journal of Physical Chemistry B,* vol.106, no.42, 10930-10934

Debackere, K. & Rappa, M. (1994) Technological communities and the diffusion of knowledge: a replication and validation, *R&D Management,* vol.24, no.4, 209-220

Department of Energy (2008) *Fiscal Year 2009 Budget-in-Brief*

Department of Energy (2007) *Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2005-2015*

Department of Energy (2006) *Targets for on-board hydrogen storage systems*

Department of Energy (2002) *National Hydrogen Energy Roadmap,* Office of Hydrogen, Fuel Cells, and Infrastructure Technologies, Washington DC

Dignum, M. & Verbong, G. (2008) The History of the Concept of the Hydrogen Economy, *SHOT Annual Meeting*

Dijk, M.M. (2010) Innovation in car mobility: co-evolution of demand and supply under sustainability pressures

Dijk, M. & Kemp, R. (2010) A framework for product market innovation paths - emergence of hybrid vehicles as an example, *International Journal of Automotive Technology and Management,* vol.10, no.1, 56-76

DOE (2009) *FY2010 Congressional Budget Request*

DOE & FreedomCAR & Fuel Partnership (2009) *Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles*

DOE (2006) Go/No-Go Decision: Pure, Undoped Single Walled Carbon Nanotubes for Vehicular Hydrogen Storage

DOE (2004) *On-board Fuel Processing Go/No-Go Decision,*

Dosi, G. & Nelson, R.R. (1994) An introduction to evolutionary theories in economics, *Journal of evolutionary economics,* vol.4, no.3, 153-172

Dosi, G. (1988) The nature of the innovative process, *Technical Change and Economic Theory,* 221-238

Dosi, G. (1982) Technological paradigms and technological trajectories, *Research policy,* vol.11, no.3, 147-162

Duwe, M. (2003) *Hydrogen for a Cleaner Europe? Only if it's green!* CAN-Europe, Greenpeace, T&E, WWF

Eames, M., McDowall, W., Hodson, M. & Marvin, S. (2006) Negotiating contested visions and place-specific expectations of the hydrogen economy, *Technology Analysis & Strategic Management,* vol.18, no.3-4, 361-374

Eisenhardt, K.M. & Tabrizi, B.N. (1995) Accelerating adaptive processes: product innovation in the global computer industry, *Administrative Science Quarterly,* vol.40, no.1, 84-110

Eisler, M.N. (2009) Getting power to the people: technological dramaturgy and the quest for the electrochemical engine, *History and Technology,* vol.25, no.1, 49-68

European Commission (2008) *European funded research on Hydrogen and Fuel Cells - review, assessment, future outlook*

European Commission (2006) *Introducing Hydrogen as an Energy Carrier,* Directorate-General for Research Sustainable Energy Systems

Faber, A. & Frenken, K. (2009) Models in evolutionary economics and environmental policy: Towards an evolutionary environmental economics, *Technological Forecasting and Social Change,* vol.76, no.4, 462-470

Felderhoff, M., Weidenthaler, C., Helmolt, R. & Eberle, U. (2007) Hydrogen storage: the remaining scientific and technological challenges, *Physical Chemistry Chemical Physics,* vol.9, no.21, 2643-2653

Fenn, J. (2007) *Understanding Gartner's Hype Cycles,* Gartner Research,

Frenette, G. & Forthoffer, D. (2009) Economic & commercial viability of hydrogen fuel cell vehicles from an automotive manufacturer perspective, *International Journal of Hydrogen Energy,* vol.34, no.9, 3578-3588

Frenken, K., Hekkert, M. & Godfroij, P. (2004) R&D portfolios in environmentally friendly automotive propulsion: Variety, competition and policy implications, *Technological Forecasting & Social Change,* vol.71, no.5, 485-507

Frenken, K., Saviotti, P.P. & Trommetter, M. (1999) Variety and niche creation in aircraft, helicopters, motorcycles and microcomputers, *Research Policy,* vol.28, no.5, 469-488

Funk, J.L. (2003) Standards, dominant designs and preferential acquisition of complementary assets through slight information advantages, *Research Policy,* vol.32, no.8, 1325-1341

Garud, R., Jain, S. & Kumaraswamy, A. (2002) Institutional entrepreneurship in the sponsorship of common technological standards: The case of Sun Microsystems and Java, *The Academy of Management Journal,* vol.45, no.1, 196-214

Garud, R. & Ahlstrom, D. (1997) Technology assessment: a socio-cognitive perspective, *Journal of Engineering and Technology Management,* vol.14, no.1, 25-48

Garud, R. & Rappa, M.A. (1994) A Socio-cognitive Model of Technology Evolution: The Case of Cochlear Implants, *Organization Science,* vol.5, no.3, 344-362

Geels, F. & Deuten, J.J. (2006) Local and global dynamics in technological development: a socio-cognitive perspective on knowledge flows and lessons from reinforced concrete, *Science and Public Policy,* vol.33, no.4, 265-275

Geels, F.W. (2010) Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective, *Research Policy*

Geels, F. & Raven, R. (2006) Non-linearity and expectations in niche-development trajectories: Ups and downs in Dutch biogas development (1973-2003), *Technology Analysis & Strategic Management,* vol.18, no.3-4, 375-392

Geels, F.W., Pieters, T. & Snelders, S. (2007) Cultural enthusiasm, resistance and the societal embedding of new technologies: Psychotropic drugs in the 20th century, *Technology Analysis & Strategic Management,* vol.19, no.2, 145-165

Geels, F.W. & Schot, J. (2007) Typology of sociotechnical transition pathways, *Research Policy,* vol.36, no.3, 399-417

Geels, F.W. (2006) Co-evolutionary and multi-level dynamics in transitions: The transformation of aviation systems and the shift from propeller to turbojet (1930-1970), *Technovation,* vol.26, no.9, 999-1016

Geels, F.W. (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, *Research Policy,* vol.31, no.8-9, 1257-1274

Glynn, S. (2002) Constructing a selection environment: competing expectations for CFC alternatives, *Research Policy,* vol.31, no.6, 935-946

Grindley, P. (1995) *Standards, strategy and policy: cases and stories,* Oxford University Press

Guice, J. (1999) Designing the future: the culture of new trends in science and technology, *Research Policy,* vol.28, no.1, 81-98

Güther, V. & Otto, A. (1999) Recent developments in hydrogen storage applications based on metal hydrides, *Journal of Alloys and Compounds,* vol.293, 889-892

Hagedoorn, J., Carayannis, E. & Alexander, J. (2001) Strange bedfellows in the personal computer industry: technology alliances between IBM and Apple, *Research Policy,* vol.30, no.5, 837-849

Hammerschmidt, A.E. (2006) Fuel Cell Propulsion of Submarines, *Advanced Naval Propulsion Symposium*

Hegger, D.L.T., Vliet, J.v. & Vliet, B.J.M. (2007) Niche management and its contribution to regime change: the case of innovation in sanitation, *Technology Analysis & Strategic Management,* vol.19, no.6, 729-746

Hekkert, M. & Van den Hoed, R. (2004) Competing technologies and the struggle towards a new dominant design: the emergence of the hybrid vehicle at the expense of the fuel cell vehicle, *Greener Management International,* vol.47, 29-44

Hekkert, M.P., Van Giessel, J.F., Ros, M., Wietschel, M. & Meeus, M.T.H. (2005) The evolution of hydrogen research: Is Germany heading for an early lock-in? *International Journal of Hydrogen Energy,* vol.30, no.10, 1045-1052

Henderson, R.M. & Clark, K.B. (1990) Architectural Innovation - The Reconfiguration of Existing Product Technologies and the Failure of Established Firms, *Administrative Science Quarterly,* vol.35, no.1, 9-30

HFP (2005) *Deployment Strategy Progress Report,* The European Hydrogen and Fuel Cell Technology Platform

Hoogma, R. (2002) *Experimenting for sustainable transport: the approach of strategic niche management,* Spon Press

Hounshell, D.A. (1985) *From the American system to mass production, 1800-1932: The development of manufacturing technology in the United States,* Johns Hopkins Univ Pr

Hultman, M. (2009) Back to the future: The dream of a perpetuum mobile in the atomic society and the hydrogen economy, *Futures,* vol.41, no.4, 226-233

IEA (2004) *In Pursuit of the Future,* National Library of Australia,

Ieromonachou, P., Potter, S. & Enoch, M. (2004) Adapting Strategic Niche Management for evaluating radical transport policies--the case of the Durham Road Access Charging Scheme, *International Journal of Transport Management,* vol.2, no.2, 75-87

Irvine, J. & Martin, B.R. (1984) Foresight in science: Picking the winners, *London: Frances Pinter,*

Islas, J. (1999) The gas turbine: a new technological paradigm in electricity generation, *Technological Forecasting and Social Change,* vol.60, no.2, 129-148

Jain, I.P., Vijay, Y.K., Malhotra, L.K. & Uppadhay, S. (1988) Hydrogen storage in the film metal-hydride - a review, *International Journal of Hydrogen Energy,* vol.13, 15-23

Kemp, R. & Soete, L. (1992) The greening of technological progress: an evolutionary perspective, *Futures,* vol.24, no.5, 437-457

Kemp, R., Schot, J. & Hoogma, R. (1998) Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management, *Technology Analysis & Strategic Management,* vol.10, no.2, 175-198

Kingdon, J.W. (1984) *Agendas,* Little, Brown and Company, Boston and Toronto

Klepper, S. (2002) The capabilities of new firms and the evolution of the US automobile industry, *Industrial and Corporate Change,* vol.11, no.4, 645-666

Konrad, K., Markard, J., Ruef, A. & Truffer, B. (2009) Strategic Responses to Hype & Disappointment: the case of stationary fuel cells, *Workshop on Expectation-building and innovation processes*

Konrad, K. (2006) The social dynamics of expectations: The interaction of collective and actor-specific expectations on electronic commerce and interactive television, *Technology Analysis & Strategic Management,* vol.18, no.3-4, 429-444

Kuhn, T.S. (1992) *The Structure of Scientific Revolutions,* University of Chicago Press, , Chicago

Lant, T.K. (1992) Aspiration Level Adaptation - An Empirical Exploration, *Management Science,* vol.38, no.5, 623-644

Latour, B. (1987) *Science in action,* Harvard University Press Cambridge, Mass,

Lee, J., Veloso, F.M., Hounshell, D.A. & Rubin, E.S. (2010) Forcing technological change: A case of automobile emissions control technology development in the US, *Technovation,* vol.30, no.4, 249-264

Levinthal, D. & March, J.G. (1981) A model of adaptive organizational search, *Journal of Economic Behavior and Organization,* vol.2, no.4, 307-333

Lichtenthaler, E. (2004) Technological change and the technology intelligence process: a case study, *Journal of Engineering and Technology Management,* vol.21, no.4, 331-348

Liebowitz, S.J. & Margolis, S.E. (1995) Path dependence, lock-in, and history, *Journal of Law, Economics, and Organization,* vol.11, 205-226

Lopolito, A., Morone, P. & Sisto, R. (2010) Innovation niches and socio-technical transition: a case study of bio-refinery production, *Futures,* vol.dx.doi.org/10.1016/j.futures.2010.03.002,

Luiten, E., van Lente, H. & Blok, K. (2006) Slow technologies and government intervention: energy efficiency in industrial process technologies, *Technovation,* vol.26, no.9, 1029-1044

Lynn, L.H., Aram, J.D. & Mohan Reddy, N. (1998) Technology communities and innovation communities, *Journal of Engineering and Technology Management,* vol.14, no.2, 129-145

Lynn, L.H., Mohan Reddy, N. & Aram, J.D. (1996) Linking technology and institutions: the innovation community framework, *Research Policy,* vol.25, no.1, 91-106

March, J.G. (1991) Exploration and exploitation in organizational learning, *Organization Science,* vol.2, no.1, 71-87

Marchetti, C. (1976) On Hydrogen and Energy Systems, *International Journal of Hydrogen Energy,* vol.1, no.1, 3-10

Markard, J. & Truffer, B. (2008) Technological innovation systems and the multi-level perspective: Towards an integrated framework, *Research Policy,* vol.37, no.4, 596-615

Marshall, A. (2006) *Next Steps for the Development of a Hydrogen Infrastructure for Road Transport in Europe*

Maskus, K.E. & McDaniel, C. (1999) Impacts of the Japanese patent system on productivity growth, *Japan and the World Economy,* vol.11, no.4, 557-574

Maus, S., Hapke, J., Ranong, C.N., Wüchner, E., Friedlmeier, G. & Wenger, D. (2008) Filling procedure for vehicles with compressed hydrogen tanks, *International Journal of Hydrogen Energy,* vol.33, no.17, 4612-4621

McConnell, V.P. (2007) Downsized footprint and material changes for GM's fourth-generation fuel cell technology, *Fuel Cells Bulletin,* vol.2007, no.1, 12-15

McDowall, W. & Eames, M. (2006) Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature, *Energy Policy,* vol.34, no.11, 1236-1250

McGrath, R.G. (1997) A Real Options Logic for Initiating Technology Positioning Investments, *Academy of Management Review,* vol.22, 974-996

Miller, R., Hobday, M., Leroux-Demers, T. & Olleros, X. (1995) Innovation in complex systems industries: the case of flight simulation, *Industrial and Corporate Change,* vol.4, no.2, 363-400

Mom, G. (2004) *The electric vehicle: technology and expectations in the automobile age,* Johns Hopkins Univ Pr

Murmann, J.P. & Frenken, K. (2006) Toward a systematic framework for research on dominant designs, technological innovations, and industrial change, *Research Policy,* vol.35, no.7, 925-952

Nelson, R.R. & Winter, S.G. (1982) *An evolutionary theory of economic change,* Belknap Press

Nelson, R.R. & Winter, S.G. (1977) In search of a useful theory of innovation, *Research Policy,* vol.6, no.1, 36-76

Nykvist, B. & Whitmarsh, L. (2008) A multi-level analysis of sustainable mobility transitions: Niche development in the UK and Sweden, *Technological Forecasting and Social Change,* vol.75, no.9, 1373-1387

Ogden, J.M. (1999) Developing an infrastructure for hydrogen vehicles: a Southern California case study, *International Journal of Hydrogen Energy,* vol.24, no.8, 709-730

O'Leary, D.E. (2008) Gartner's hype cycle and information system research issues, *International Journal of Accounting Information Systems,* vol.9, no.4, 240-252

Oltra, V. & Saint Jean, M. (2009) Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis, *Journal of Cleaner Production,* vol.17, no.2, 201-213

Pavitt, K. (1982) R&D, patenting and innovative activities: a statistical exploration, *Research Policy,* vol.11, 33-51

Peschka, W. (1987) The status of handling and storage techniques for liquid hydrogen in motor vehicles, *International Journal of Hydrogen Energy,* vol.12, no.11, 753-764

Pezat, M., Darriet, B. & Hagenmuller, P. (1980) A comparative study of magnesium-rich rare-earth based alloys for hydrogen storage, *Journal of the Less-Common Metals,* vol.74, 427-434

Phaal, R., Farrukh, C.J.P. & Probert, D.R. (2004) Technology roadmapping - A planning framework for evolution and revolution, *Technological Forecasting & Social Change,* vol.71, no.1-2, 5-26

Pilkington, A., Lee, L.L., Chan, C.K. & Ramakrishna, S. (2009) Defining key inventors: A comparison of fuel cell and nanotechnology industries, *Technological Forecasting and Social Change,* vol.76, no.1, 118-127

Pilkington, A. (2004) Technology portfolio alignment as an indicator of commercialisation: an investigation of fuel cell patenting, *Technovation,* vol.24, no.10, 761-771

Pilkington, A., Dyerson, R. & Tissier, O. (2002) The electric vehicle: Patent data as indicators of technological development, *World Patent Information,* vol.24, no.1, 5-12

Pinch, T.J. & Bijker, W.E. (1984) The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other, *Social Studies of Science,* vol.14, no.3, 399

Propp, T. & Rip, A. (2006) Assessment tools for the management of new and emerging science and technology: state-of-the-art and research gaps, *TA NanoNed Working Papers,* no.Working Paper No.1

Rappa, M.A. & Debackere, K. (1992) Technological Communities and the Diffusion of Knowledge, *R & D Management,* vol.22, no.3, 209-220

Rappert, B. (1999) Rationalising the future? Foresight in science and technology policy co-ordination, *Futures,* vol.31, no.6, 527-545

Raven, R. & Geels, F. (2010) Socio-cognitive evolution in niche development: Comparative analysis of biogas development in Denmark and the Netherlands (1973-2004), *Technovation,* vol.30, no.2, 87-99

Raven, R. (2004) Implementation of manure digestion and co-combustion in the Dutch electricity regime: a multi-level analysis of market implementation in the Netherlands, *Energy Policy,* vol.32, no.1, 29-39

Reger, G. (2001) Technology foresight in companies: from an indicator to a network and process perspective, *Technology Analysis & Strategic Management,* vol.13, no.4, 533-553

Rifkin, J. (2002) *The Hydrogen Economy,* Tarcher/Penguin, New York

Rip, A. (2006) Folk Theories of Nanotechnologists, *Science as Culture,* vol.15, no.4, 349-365

Rip, A. & Schot, J.W. (2002) "Identifying Loci for Influencing the Dynamics of Technological Development", in *Shaping Technology, Guiding Policy: Concepts, Spaces and Tools,* eds. K.H. Sørensen & R. Williams,Edward Elgar, Cheltenham

Rip, A., Misa, T.J. & Schot, J. (1995) *Managing Technology in Society: The Approach of Constructive Technology Assessment,* Pinter Publishers, London

Romm, J. (2006) The car and fuel of the future, *Energy Policy,* vol.34, no.17, 2609-2614

Romm, J.J. (2005) *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate,* Island Press

Romm, J.J. (2004) The hype about hydrogen, *Issues in Science and Technology,* vol.20, no.3, 74-81

Rose, R., Gangi, J. & Curtin, S. (2008) *International Hydrogen and Fuel Cell Policy and Funding,* Fuel Cells 2000

Rosenberg, N. (1976) On technological expectations, *The Economic Journal,* 523-535

Rosenberg, N. (1982) *Inside the Black Box: Technology and Economics,* Cambridge University Press, Cambridge

Rosenkopf, L. & Nerkar, A. (1999) "On the Complexity of Technological Evolution: Exploring Coevolution Within and Across Hierarchical Levels in Optical Disc Technology", in *Variations in Organization Science: In Honor of D. T. Campbell,* Sage Publications

Rosenkopf, L. & Tushman, M.L. (1998) The coevolution of community networks and technology: Lessons from the flight simulation industry, *Industrial and Corporate Change,* vol.7, no.2, 311-346

Ruef, A. & Markard, J. (2010) What happens after a hype? How changing expectations affected innovation activities in the case of stationary fuel cells, *Technology Analysis & Strategic Management,* vol.22, no.3, 317–338

Sakintuna, B., Lamari-Darkrim, F. & Hirscher, M. (2007) Metal hydride materials for solid hydrogen storage: A review, *International Journal of Hydrogen Energy,* vol.32, no.9, 1121-1140

Sandy Thomas, C.E. (2009) Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles, *International Journal of Hydrogen Energy,* vol.34, no.23, 9279-9296

Schaeffer, G.J. (1998) *Fuel Cells for the Future: A contribution to technology forecasting from a technology-dynamics perspective,* University of Twente, , Enschede

Schlapbach, L. & Zuttel, A. (2001) Hydrogen-storage materials for mobile applications, *Nature,* vol.414, no.6861, 353-8

Schot, J. & Geels, F.W. (2008) Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy, *Technology Analysis & Strategic Management,* vol.20, no.5, 537-554

Schot, J. & Geels, F.W. (2007) Niches in evolutionary theories of technical change, *Journal of Evolutionary Economics,* vol.17, no.5, 605-622

Schot, J.W. (1992) Constructive Technology -Assessment and Technology Dynamics - The Case of Clean Technologies, *Science Technology & Human Values,* vol.17, no.1, 36-56

Schot, J., Hoogma, R. & Elzen, B. (1994) Strategies for shifting technological systems: The case of the automobile system, *Futures,* vol.26, no.10, 1060-1076

Service, R.F. (2009) Hydrogen Cars: Fad or the Future? *Science,* vol.324, no.5932, 1257-1259

Seymour, E.H., Borges, F.C. & Fernandes, R. (2007) Indicators of European public research in hydrogen and fuel cells--An input-output analysis, *International Journal of Hydrogen Energy,* vol.32, no.15, 3212-3222

Shehabuddeen, N., Probert, D. & Phaal, R. (2006) From theory to practice: challenges in operationalising a technology selection framework, *Technovation,* vol.26, no.3, 324-335

Shove, E. & Walker, G. (2007) CAUTION! Transitions ahead: politics, practice, and sustainable transition management, *Environment and Planning A,* vol.39, no.4, 763-770

Smil, V. (2000) Perils of long-range energy forecasting: Reflections on looking far ahead, *Technological Forecasting and Social Change,* vol.65, no.3, 251-264

Smith, A. (2007) Translating sustainabilities between green niches and socio-technical regimes, *Technology Analysis and Strategic Management,* vol.19, no.4, 427-450

Smith, A., Stirling, A. & Berkhout, F. (2005) The governance of sustainable socio-technical transitions, *Research Policy,* vol.34, no.10, 1491-1510

Smith, A., Voß, J. & Grin, J. (2010) Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges, *Research Policy,* vol.39, no.4, 435-448

Solomon, B.D. & Banerjee, A. (2006) A global survey of hydrogen energy research, development and policy, *Energy Policy,* vol.34, no.7, 781-792

Sperling, D. & Ogden, J. (2004) The Hope for Hydrogen, *Issues in Science and Technology,* vol.20, no.3, 82-86

Suarez, F.F. (2004) Battles for technological dominance: an integrative framework, *Research Policy,* vol.33, no.2, 271-286

Suarez, F.F. & Utterback, J.M. (1995) Dominant designs and the survival of firms, *Strategic Management Journal,* vol.16, 415-430

Suchman, L., Trigg, R. & Blomberg, J. (2002) Working artefacts: ethnomethods of the prototype, *The British journal of sociology,* vol.53, no.2, 163-179

Suurs, R.A.A. (2009) *Motors of sustainable innovation: Towards a theory on the dynamics of technological innovation systems,* Utrecht University

Suurs, R.A.A., Hekkert, M.P. & Smits, R.E.H.M. (2009) Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies, *International Journal of Hydrogen Energy,* vol.34, no.24, 9639-9654

Thomke, S., von Hippel, E. & Franke, R. (1998) Modes of experimentation: an innovation process - and competitive - variable, *Research Policy,* vol.27, no.3, 315-332

Thomke, S.H. (1998) Simulation, learning and R&D performance: Evidence from automotive development, *Research Policy,* vol.27, no.1, 55-74

Toulmin, S.E. (1958) *The Uses of Argument,* Cambridge University Press,

Tushman, M.L. & Anderson, P. (1986) Technological discontinuities and organizational environments, *Administrative Science Quarterly,* 439-465

Unruh, G.C. (2000) Understanding carbon lock-in, *Energy Policy,* vol.28, no.12, 817-830

Utterback, J.M. (1994) *Mastering the Dynamics of Innovation,* Harvard Business School Press, , Boston

Vaitheeswaran, V. & Carson, I. (2008) *ZOOM: The Global Race to Fuel the Car of the Future,* Penguin Books, London

van Bree, B., Verbong, G.P.J. & Kramer, G.J. (2010) A multi-level perspective on the introduction of hydrogen and battery-electric vehicles, *Technological Forecasting and Social Change,* vol.77, no.4, 529-540

van den Belt, H. & Rip, A. (1987) "The Nelson-Winter-Dosi Model and Synthetic Dye Chemistry", in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology,* MIT Press, Cambridge

van den Bergh, J.C.J.M., Faber, A., Idenburg, A.M. & Oosterhuis, F.H. (2006) Survival of the greenest: evolutionary economics and policies for energy innovation, *Journal of Integrative Environmental Sciences,* vol.3, no.1, 57-71

van den Bossche, P., Vergels, F., van Mierlo, J., Matheys, J. & van Autenboer, W. (2006) SUBAT: An assessment of sustainable battery technology, *Journal of Power Sources,* vol.162, no.2, 913-919

van den Hoed, R. (2007) Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry, *Journal of Cleaner Production,* vol.15, no.11-12, 1014-1021

van den Hoed, R. (2005) Commitment to fuel cell technology? How to interpret carmakers' efforts in this radical technology, *Journal of Power Sources,* vol.141, no.2, 265-271

van der Duin, P. (2006) *Qualitative futures research for innovation,* Eburon Uitgeverij BV

van der Laak, W.W.M., Raven, R. & Verbong, G.P.J. (2007) Strategic niche management for biofuels: Analysing past experiments for developing new biofuel policies, *Energy Policy,* vol.35, no.6, 3213-3225

van Eijck, J. & Romijn, H. (2008) Prospects for Jatropha biofuels in Tanzania: An analysis with Strategic Niche Management, *Energy Policy,* vol.36, no.1, 311-325 van Lente, H. & Bakker, S. (2010) Competing expectations: the case of hydrogen storage technologies, *Technology Analysis & Strategic Management,* vol.22, no.6, 693-709

van Lente, H. & Rip, A. (1998a) "Expectations in technological developments: An example of prospective structures to be filled in by agency", in *Getting New Technologies Together. Studies in Making Sociotechnical Order,* , eds. C. Disco & B. van der Meulen,Walter de Gruyter, Berlin, pp. 203-231

van Lente, H. & Rip, A. (1998b) The rise of membrane technology: From rhetorics to social reality, *Social Studies of Science,* vol.28, no.2, 221-254

van Lente, H. (1993) *Promising Technology: The Dynamics of Expectations in Technological Developments,* Twente University, , Enschede

van Lente, H. (2000) Forceful Futures: From Promise to Requirement, *N.Brown, B.Rappert & A.Webster, Contested Futures.A sociology of prospective technoscience.London, Ashgate Publishing Company,* 43-64

Verbong, G., Geels, F.W. & Raven, R. (2008) Multi-niche analysis of dynamics and policies in Dutch renewable energy innovation journeys (1970–2006): hype-cycles, closed networks and technology-focused learning, *Technology Analysis & Strategic Management,* vol.20, no.5, 555-573

Verbong, G. & Geels, F. (2007) The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960-2004), *Energy Policy,* vol.35, no.2, 1025-1037

Vergragt, P.J. (1988) The social shaping of industrial innovations, *Social Studies of Science,* vol.18, no.3, 483-513

Vermeulen, U. (2006) *Waterstof Brandstof voor Transities,* Platform Nieuw Gas, Werkgroep Waterstof

Wade, J. (1995) Dynamics of Organizational Communities and Technological Bandwagons - An Empirical Investigation of Community Evolution in the Microprocessor Market, *Strategic Management Journal,* vol.16, 111-133

Watanabe, C., Tsuji, Y.S. & Griffy-Brown, C. (2001) Patent statistics: deciphering a 'real' versus a 'pseudo' proxy of innovation, *Technovation,* vol.21, no.12, 783-790

Webster, A. (1999) Technologies in transition, policies in transition: foresight in the risk society, *Technovation,* vol.19, no.6-7, 413-421

Weinstein, M. (1990) Towards an account of argumentation in science, *Argumentation,* vol.4, no.3, 269-298

Wilkie, A. (2008) Prototyping Health Care Users, *4S/EASST 2008 Joint Annual Meeting*Rotterdam

Willinger, M. & Zuscovitc, E. (1993) Efficience, irréversibilités et constitution des technologies, *Revue d'économie industrielle,* vol.65, no.1, 7-22

Wüstenhagen, R., Wuebker, R., Bürer, M.J. & Goddard, D. (2009) "Financing Fuel-Cell Market Development: Exploring the Role of Expectation Dynamics in Venture Capital Investment", in *Innovation, Markets, and Sustainable Energy: The Challenge of Hydrogen and Fuel Cells,* eds. S. Pogutz, A. Russo & P. Migliavacca,Edward Elgar, Cheltenham (UK) and Lyme (US)

Yergin, D. (1991) *The Prize: The Epic Quest for Oil,* Simon & Schuster Ltd, , New York

Summary

Firms and governments can support only a limited number of emerging technologies. Some emerging technologies receive support for further development while others are discarded. But how do decision makers in firms and governments assess which of the options earns their support? Straightforward assessments of prices and performance levels can not be sufficient as emerging technologies are, by definition, in an early stage of development and have not reached their maximum levels of performance yet. It is therefore not so much of interest which of the options performs best at any point in time, but rather which of the options will eventually perform best in the future. In this thesis it is thus questioned:

How do emerging technologies compete?

The starting point of this thesis is that this competition is based on expectations about future price and performance levels. It is studied how both the relevant decision makers and the technology developers themselves deal with these expectations about the different options.

The development of the hydrogen car takes up a central position in this thesis. The hydrogen car is one of the contenders in the race to become 'the car of the future'. The car of the future is envisioned to be a low- or zero-emissions vehicle and it supposed to be independent of fossil fuels. While the hydrogen car is indeed in competition with the other contenders, most notably with the battery-electric vehicle, there is also competition between different configurations of the hydrogen car itself. Hydrogen can be converted to power in an internal combustion engine, but it can also be used by means of a fuel cell that generates electricity. Next to that, hydrogen storage is another major issue as enough hydrogen needs to be stored on-board the car to provide it with a sufficient drive range. Next to gaseous and liquid hydrogen storage systems, solid and liquid materials can also be used as storage media.

To study the competition between emerging technologies, the quasi-evolutionary model of technological development is used (Van den Belt and Rip 1987, Schot 1992). It builds on the evolutionary economists' conceptualization of technological innovation as a process of variation and selection. The quasi-evolutionary model however adds that both variation and selection are not blind but rely very much on anticipations of the actors that are involved. They have some understanding of which variations are promising and what the selection environment looks like. The quasi-evolutionary model addresses the competition between technological options and it embraces the role of expectations in the innovation process. It does so however only in rather unspecific terms. A related body of literature, the sociology of expectations, has taken on the task of explicating the role of expectations in innovation processes (van Lente 1993, Borup et al 2006) and it is used extensively in this thesis. But, it has been less interested in competing expectations and tends to obscure the role of agency that is involved in the shaping and assessment of expectations. An essential link is provided by Garud and Ahlstrom (1997). They argue that a socio-cognitive 'game' is played between, on the one hand, insiders that create and 'enact' a technological option ('enactors' as suggested by Rip (2006)) and, on the other hand, outsiders that select technologies according to their own criteria ('selectors'). Furthermore, the enactors are not just individuals and together they form so-called technological communities (Rappa and Debackere 1992) of actors that work on a shared technological option. The members of these communities actively engage in expectations work to convince selectors of the potential of their option. At the same time, the selectors perform expectations work to assess the different expectations and determine which of the variations are indeed promising.
Following the insights from quasi-evolution, expectations and communities, the central research question can be broken down into two sub questions:

How do enactors try to shape expectations of their technological options?

How do selectors make assessments of those expectations?

Different (sub-) cases were selected to answer these questions and unravel the dynamics of competing expectations in relation to the hydrogen car. These cases were selected on the basis of two dimensions of the competition between emerging technologies. The first axis relates to the distinction between the enactors and the selectors. The second axis relates to the distinction between the system-level and the component-level. Together these axes shape four quadrants that had to be covered by the different cases. The seven empirical chapters are devoted to the individual case studies.

In **Chapter 2** the expectations work of enactors and selectors is described in a case study on the community of researchers that develop metal hydrides for the on-board storage of hydrogen. It is shown how this community conveys the message that metal hydrides are the most promising solution. The core of their message is not that metal hydrides are the best performing option, but rather that they are the only option that has the potential to improve further, whereas the other solutions are

fundamentally limited in terms of storage capacity. The selectors have accepted this message and have given the metal hydrides community a wide mandate for their work. That is, as long as they can show an increase in the performance levels, they are rather free to choose the materials they wish to study and develop.
This chapter also introduces the 'arenas of expectations' framework as a means to study and understand the exchange and assessment of technological expectations. In arenas of expectations 'enactors' of particular technological variations voice and maintain expectations, while 'selectors' will compare and assess the competing claims. Thereby the arenas form the linchpin between variation and selection. Essential here is that the expectations work is not just a bilateral process between one enactor and one selector. Rather, the competition between emerging technologies involves many different actors and a wide variety of earlier exchanges and assessments of technological expectations, including those that succeeded and those that failed

The community of metal hydrides researchers features again in the case study in **Chapter 3**. In this chapter the notion of competing expectations is elaborated further and an extension to the 'phases of innovation' model of Utterback (1994) is proposed. Whereas the Utterback-model, like many other models of innovation, takes into account only the competition between technological options as far as it is takes place in the market, in this chapter it is argued that a phase of expectations precedes the market phases. The presented case study consists of an analysis of 263 scientific papers from the metal hydrides community. With the help of Stephen Toulmin's scheme or argumentation (1958) it is shown that, and how, this community of scientists makes a case for metal hydrides as the most promising storage material. Again it becomes clear that expectations work is just as much about criticizing the competing options as it is about stressing the future potential of one's own option. The chapter concludes with a characterisation of the 'expectations' phase of competing technologies.

In contrast with the earlier chapters, the focus of **Chapter 4** lies on the side of the selectors. Here pre-market competition between different hydrogen car design options is studied in the context of the automotive industry. The notion of dominant designs is used as starting point. It refers to dominance in the market, of a specific design, which is assumed to be dominant due to market selection forces and it thus ignores the possible selection that takes place in pre-market R&D stages of technological trajectories. In this chapter an answer is sought to the question whether selection of a dominant design can also take place in the pre-market phase. Furthermore it is studied what selection criteria apply when actual market criteria are absent. This is done through an analysis of prototyping trajectories for hydrogen vehicles.
To study the dynamics of pre-market variation and selection, data on 224 hydrogen passenger car prototypes were included in a database. The analysis shows that the design configurations of the prototypes have indeed converged over time towards a combination of a PEM fuel cell and a high pressure, gaseous, storage system. In the absence of market forces, it is a combination of current and expected technological performance characteristics, anticipated regulations and strategic manoeuvring

of the firms that guides the selection of the emerging dominant design. These technological and strategic factors have co-evolved and reinforced each other. Economies of scale present, mostly with regard to infrastructure build-up, an incentive to the industry to select a single configuration already before market introduction takes place. And, next to that, the most active firms give the strongest signals about their expectations of their designs, as they produce the largest numbers of prototypes, and following firms tend to conform to these designs in later stages. This behaviour confirms the assumption that prototypes are more than just test objects. They are actively used as expectations tools towards consumers, governments and industry rivals.

In **Chapter 5** it is studied whether the same dynamics can be traced in car manufacturers' patent portfolios. That is, one could assume that the technological options that were used in the hydrogen prototype vehicles can also be found in the firm's patent portfolios. And, that the convergence in the prototype designs is also reflected in narrowing patent portfolios. To quantify the extent to which the firms widen or narrow their portfolios, a measure of entropy was used. It is found that whereas the patent portfolios do converge to PEM fuel cells, for hydrogen conversion, the entropy continues to increase with respect to hydrogen storage options. These findings raise questions about the commercialization of hydrogen vehicles, as the industry is still searching for promising storage methods. And it is argued that indecision with regard to storage methods is problematic for the build-up of a hydrogen refilling infrastructure: different storage methods require different refilling systems.

Chapter 6 deals with the question why some technological expectations are thought to be credible and others are not on both the component level as well as the system level. A case study on the US Department of Energy's (DOE) Hydrogen Program is performed to study how both enactors and selectors make assessments of the credibility of technological expectations. The case study is based on DOE documents, meeting minutes, and short interviews with DOE staff members.

In the chapter it is shown how credible expectations build on three arguments in favour of the promising option. First there is the technology's current level of performance and its historical progress towards that level. Second a path forward is constructed to argue that even higher levels of performance can be achieved. And third, a target or end-goal is constructed that the technology is expected, or supposed, to meet and this end-goal relates to perceived societal needs. All three elements can, and often are, subject of contestation and competing options will provide the same type of arguments and relate to the same societal needs.

In a hierarchy of systems and enabling components, the system is more credible when its enabling components are thought to be promising and vice versa. It is shown that increased pressure on the envisioned hydrogen vision, as a consequence of disappointing outcomes, has resulted in more stringent selection of enabling technologies. In other words, the 'losers' are dropped from the hydrogen research portfolio in order to increase the credibility of the system as a whole.

The decline of attention for the hydrogen car cannot be understood in isolation from the recent comeback of the battery-electric vehicle. This competition on the system level is the topic of study in **Chapter 7**. Conceptually this chapter draws from the notion of 'technological niches' which has proved useful to understand and account for the emergence of radical innovations. Most studies, however, only deal with the development of single emerging technologies. In this chapter the competition between multiple niche technologies is addressed. Within the niche of the 'car of the future' two designs compete: the battery-electric and the hydrogen car. While both are shielded from regular market forces, they have to compete in terms of R&D funding, supportive regulation and infrastructure build-up. In our case study we trace this competition in terms of design rules and expectations and show how attention for both options has alternated in three phases, which follow the high hopes and subsequent disappointments of the different component technologies. Whereas there is room for simultaneously developed, multiple options on the local level, on the global level attention and expectations seem much more focused on either the one or the other.

The recent disappointment with regard to hydrogen cars and the decline of attention are partly due to the high expectations that currently surround the battery-electric vehicle. However, as it is argued in **Chapter 8** the hydrogen community itself, and especially the car industry, is also responsible for these developments. In this chapter the question is asked to what extent the car industry has created the hype and how it has done so. The industry's role is studied through their prototyping activities and accompanying statements on market entry. It is concluded that the car industry has indeed inflated the hype, especially through its public statements on market release after the turn of the millennium. Furthermore, it can be concluded that the industry has shown a double repertoire of both highly optimistic and more modest statements. It is argued that statements are used deliberately to serve the industry's interests whenever needed. Without neglecting the positive influence of technological hype on public policy and private funding for R&D efforts, more modest promises could serve the development of sustainable mobility better. For policy makers the challenge is thus to remain open to different options instead of following hypes and disappointments as they come and go.

In the concluding chapter, the findings from the seven empirical chapters are brought together. First of all the notion of 'arenas of expectations' is elaborated upon. They are defined as socio-cognitive spheres in which a wide variety of competing expectations is brought together and in which expectations and their assessments from the past and from different sources accumulate. Arenas can be defined on multiple levels. In the hydrogen storage arena for instance, a battle is fought between the competing storage systems and in the arena for the car of the future the competition between the hydrogen and the battery-electric vehicle takes place. Furthermore, it is argued that enactors and selectors are not fixed to their positions but that they perform roles and that an actor can play different roles in different contexts. An actor can first act as a selector and, after a selection decision is made, enact the option from then onwards. And, as was highlighted in the chapter that dealt with the DOE Hydrogen Program, in a hierarchy of technological systems and components, those who enact the system (enaction upwards) may very well be selectors of the different components that make up the system (selection downwards).

Three major conclusions are drawn in relation to the first sub question about the role of the enactors. First of all, the expectations work of an enacting community is not limited to its own option. Next to feeding expectations of its own option, the competing options are frequently criticised and their lack of future potential is stressed. Second, the enactors are aware of the risks of overpromising and realise that overly optimistic statements may, in the end, result in disappointment on the side of their sponsors. One strategy of avoiding this risk is to refrain from quantified promises, as these are more fallible than qualitative promises. And third, in times of low expectations, after a hype for instance, the enactors tend to focus more on short term opportunities and promises, rather than on far fetched long term expectations. Thereby they anticipate the changed selection criteria of the selectors.

With regard to the second sub question it is concluded that the selectors maintain portfolios of options that are promising in their view rather than placing all bets on a single option alone. The main criteria in their assessments of promises and expectations are respectively the historical progress of the options, arguments for a path forward to higher levels of performance or cost reductions and the attainability of certain end goals that the selectors have in mind. As a result, those options that fail to meet these criteria are dropped from the portfolio. In other words, technology selection is not so much a question of picking winners, but rather one of dropping losers.

The roles of enactor and selector are interrelated and so is the process of enaction and selection. A main conclusion to this thesis is that selectors tend to narrow their portfolios in times of low general expectations. They do so not only because funds are limited, but also because a wide portfolio of options signals that none of the options is truly convincing. On top of that, every expectation that is voiced is a statement about current lack of performance.

The contributions of this thesis to different strands in innovation studies are also highlighted in the final chapter. First of all, to the sociology of expectations this thesis adds an understanding of the role of agency in the emergence of collective expectations. Especially the role of the selectors is important in this respect as they distinguish, in the wide varieties of technological expectations that are put to the fore, between the credible and the incredible expectations. Furthermore, a number of quantifications of expectations are added to this otherwise predominantly qualitative body of literature: patents, prototypes, and statements from scientists and car manufacturers.

The literature on competing technologies and designs is preoccupied with competition in the market. It thereby tends to ignore the competition that takes place in the pre-market phase and the selection criteria that apply then. In the absence of market forces, it is a combination of current and expected technological performance characteristics, anticipated regulations and strategic manoeuvring of firms that guides the selection in this phase.

In relation to the literature on sociotechnical transitions, it is argued in this thesis that a thorough understanding is still lacking when it comes to competing transition trajectories. It was shown that hydrogen and battery-electric vehicles compete for attention and funding and that disappointments with one option create a window of opportunity for the other. This may result in unsteady trajectories and that in turn may lead to high societal costs and hampered innovation processes. And, it was shown that convergence of design rules, a form of articulation as it is called in this body of literature, does not necessarily result in collective positive expectations.

Finally a number of suggestions are provided for both enactors and selectors. Even though it is still somewhat questionable if and to what extent the role of hype and disappointment are truly detrimental to the development of hydrogen vehicles, it is worthwhile to consider what forms of expectations management could help to smoothen innovation trajectory. First of all, it is argued that enactors could in theory choose to voice less optimistic expectations in order to avoid hype. But, along the lines of the 'tragedy of the commons' dilemma, it is not likely that individual enactors will do so. Each has its own incentive to voice highly positive expectations, in order to attract funding. The consequences of disappointment will by and large affect the entire community. Instead, it is suggested that it is really up to the selectors to refrain from following each hype as it comes and goes. The most obvious way to do so is to develop policies that stimulate, or even force, innovation without explicit technological choices. The Californian zero-emission vehicles mandate was technology-agnostic, and so is the EU regulation on fleet-average emission standards. Such regulations trigger demand for zero- or low-emission vehicles and force automakers to innovate without selecting a certain option.

To conclude, the hydrogen car has gone through phases of hype and disappointment more than once and even though some have declared the hydrogen car dead for now, to discard it altogether would be an undervaluation of the resilience of the wider hydrogen vision and its enactors.

Samenvatting

Overheden en bedrijven kunnen slechts een beperkt aantal emergente technologieën ondersteunen. Sommige technologieën zullen daardoor steun krijgen, anderen worden afgedankt. Maar hoe worden deze keuzes gemaakt in bedrijven en overheden? Het simpelweg beoordelen van kosten en prestaties is niet voldoende. Emergente technologieën zijn per definitie nog niet uitontwikkeld en hebben nog niet hun maximale prestatieniveau bereikt. Het is voor deze overheden en bedrijven daarom niet zozeer van belang welke van de opties op enig moment het beste scoort, maar juist welke het beste zal scoren in de toekomst. In deze thesis luidt de vraag dus:

Hoe concurreren emergente technologieën?

Het uitgangspunt bij de beantwoording van deze vraag is dat de competitie tussen emergente technologieën gebaseerd moet zijn op verwachtingen over toekomstige prijs- en prestatieniveaus. Onderzocht wordt hoe zowel de relevante beslissers als de technologieontwikkelaars omgaan met deze verwachtingen van de verschillende opties.

Centraal hierbij staat de ontwikkeling van de waterstofauto. Dit type auto, waarin waterstof als brandstof dient, is een van de kandidaten in de strijd om de 'auto van de toekomst' te worden. De auto van de toekomst wordt geacht een niet of nauwelijks vervuilende auto te zijn die bovendien niet afhankelijk is van fossiele brandstoffen. De waterstofauto is een van de kandidaten in deze competitie en concurreert dus onder andere met de batterij-elektrische auto. En tegelijkertijd is er ook onderlinge concurrentie tussen verschillende configuraties van de waterstofauto zelf. Zo zijn er twee mogelijkheden voor de zogenaamde conversie van waterstof in een bruikbare vorm van energie, respectievelijk de verbrandingsmotor en de brandstofcel. En daarnaast zijn er verschillende mogelijkheden om waterstof op te slaan in de auto. Dit is een cruciale component omdat de actieradius van de auto's grotendeels bepaald wordt door de hoeveelheid waterstof die getankt kan worden.

Om de competitie tussen emergente technologieën te bestuderen wordt gebruik gemaakt van het quasi-evolutionaire model van technologieontwikkeling (Van den Belt and Rip 1987, Schot 1992). Dit model bouwt voort op eerdere evolutionaire economische modellen waarin technologische innovatie wordt beschouwd als een proces van variatie en selectie. Het quasi-evolutionaire model voegt hieraan toe dat, in het geval van innovatie, zowel variatie als selectie niet blind plaatsvindt, maar juist het gevolg is van anticipaties van de betrokken actoren. Zij maken bijvoorbeeld inschattingen over beloftevolle variaties en de criteria die zullen gelden in de selectieomgeving. Het quasi-evolutionaire model omarmt dus de rol van verwachtingen in de competitie tussen emergente technologieën, dit doet het echter slechts in weinig specifieke bewoordingen. In de zogenaamde sociologie van verwachtingen is de rol van verwachtingen in innovatieprocessen verder uitgewerkt (van Lente 1993, Borup et al 2006) en hier wordt in deze thesis dan ook nadrukkelijk gebruik van gemaakt. Echter, in de sociologie van verwachtingen wordt nauwelijks aandacht besteed aan concurrerende technologieën en de rol van actoren (*agency*) in de vorming en beoordeling van verwachtingen is minder zichtbaar geworden. In zekere zin vormt een paper van Garud en Ahlstrom (1997) de ontbrekende schakel. Zij stellen dat een sociaal-cognitief 'spel' wordt gespeeld tussen, aan de ene kant, insiders die een zekere technologische optie ontwikkelen en 'opvoeren' (Engels: *to enact*). En aan de andere kant, relatieve buitenstaanders die aan de hand van hun specifieke criteria opties selecteren. Rip (2006) stelde voor deze groepen, respectievelijk *enactors* en *selectors* te noemen.

De enactors, rondom een specifieke optie, vormen gezamenlijk een zogenaamde technologische gemeenschap (*technological community*, Rappa en Debackere 1992). De leden van de gemeenschap voeren verwachtingenwerk uit om selectors te overtuigen van de potentie en belofte van hun optie. Tegelijkertijd voeren de selectors ook verwachtingenwerk uit om te bepalen welke opties daadwerkelijk beloftevol zijn.
Aan de hand van de genoemde elementen, quasi-evolutie, verwachtingen en gemeenschappen is de onderzoeksvraag gesplitst in twee deelvragen:

Hoe proberen enactors verwachtingen van hun optie vorm te geven?

Hoe beoordelen selectors deze verwachtingen?

Om deze vragen te beantwoorden en de dynamiek van concurrerende verwachtingen bloot te leggen, is een aantal (sub-)cases binnen het domein van de ontwikkeling van de waterstofauto onderzocht. Deze zijn geselecteerd op basis van twee relevante onderscheiden. Ten eerste is er het zojuist gemaakte onderscheid tussen enactors en selectors. Ten tweede kan een onderscheid gemaakt worden tussen competitie die plaatsvindt op systeemniveau en competitie die plaatsvindt op het niveau van componenten. Samen vormen zij vier kwadranten die in de cases aan bod moesten komen. De zeven empirische hoofdstukken beschrijven elk een van de cases die zijn onderzocht.

In **Hoofdstuk 2** wordt het verwachtingenwerk van enactors en selectors beschreven aan de hand van de gemeenschap van onderzoekers die werken aan de ontwikkeling van metaalhydriden die kunnen dienen als medium voor waterstofopslag. Deze vorm van waterstofopslag is veel complexer en presteert momenteel minder goed dan bijvoorbeeld gasvormige opslag, maar de onderzoekers stellen dat er nog veel ruimte voor verbetering is. Dit in tegenstelling tot de meer eenvoudige opslagmethoden die hun limiet bereikt hebben. Het verwachtingenwerk van deze gemeenschap heeft dus niet alleen betrekking op de metaalhydriden zelf, waarom deze beloftevol zijn, maar ook op de concurrentie. Het belangrijkste argument is dat verdere verbetering van gasvormige opslag, en hetzelfde geldt voor vloeibare opslag, beperkt wordt door de wetten van de thermodynamica. Hun selectors hebben deze verwachting geaccepteerd en als gevolg daarvan heeft deze gemeenschap een ruim mandaat gekregen voor verder onderzoek. Van belang hierbij is wel dat deze gemeenschap zelf voldoende vooruitgang kan aantonen.

Op conceptueel niveau introduceert dit hoofdstuk de zogenaamde 'Arena's van Verwachtingen'. Dit concept dient als raamwerk voor het bestuderen en begrijpen van de uitwisseling en beoordeling van verwachtingen. De arena's zijn als het ware het slagveld waar de competitie plaatsvindt en waar de enactors hun verwachtingen en beloftes in de strijd werpen en waar de selectors beoordelen welke verwachtingen het sterkst en meest geloofwaardig zijn. Hiermee zijn de arena's van verwachtingen de schakel tussen variatie en selectie van emergente technologieën. Essentieel is hier dat de uitwisseling en beoordeling van verwachtingen niet een enkelvoudig en bilateraal proces is tussen een enkele enactor en een enkele selector. In de competitie tussen verschillende technologieën, en dus het verwachtingenwerk, zijn juist zeer veel verschillende actoren betrokken en deze speelt zich af gedurende een lange periode. Hierdoor vind er accumulatie plaats van opeenvolgende verwachtingen en spelen eerdere geslaagde of gefaalde verwachtingen een grote rol.

De gemeenschap van metaalhydriden onderzoekers komt ook aan bod in **Hoofdstuk 3** waarin de notie van concurrerende verwachtingen verder wordt uitgewerkt en waarin ook een uitbreiding van het 'fases van innovatie'-model van Utterback (1994) wordt voorgesteld. Het model van Utterback, net als veel andere innovatiemodellen, heeft alleen oog voor competitie tussen verschillende technologieën voor zover deze zich in de markt voltrekt. In dit hoofdstuk wordt voorgesteld om dit model uit te breiden met een eerdere fase, namelijk de verwachtingenfase. Dit argument wordt onderbouwd aan de hand van een analyse van 263 wetenschappelijke artikelen van metaalhydriden onderzoekers. Gebruikmakend van Toulmin's argumentatieschema (1958) wordt getoond hoe deze gemeenschap verwachtingen probeert te scheppen en hoe zij zo competitie voeren met andere opties. Weer wordt duidelijk dat verwachtingenwerk net zozeer gaat over het bekritiseren van de concurrerende opties als over het benadrukken van de eigen belofte. Het hoofdstuk sluit af met een karakterisering van de voorstelde verwachtingenfase.

Waar de eerste twee empirische hoofdstukken vooral betrekking hadden op de enactors, ligt de nadruk in **Hoodstuk 4** op de selectors. De competitie tussen verschillende componenten wordt hier bestudeerd in de context van de auto-industrie en het conceptuele uitgangspunt is de notie van dominante ontwerpen (dominant designs). De meeste industrieën kennen een dominant ontwerp dat geselecteerd is in de loop van een fase van competitie waarin nog meerdere ontwerpen naast elkaar bestonden. De gangbare literatuur over deze competitie, waar het Utterback-model deel van uitmaakt, gaat echter voorbij aan de strijd die plaatsvindt voordat marktintroductie heeft plaatsgevonden. In dit hoofdstuk wordt onderzocht in hoeverre soortgelijke selectie ook al plaatsvindt in de ontwikkelingsfase en welke criteria en mechanismen dan doorslaggevend zijn. Dit wordt gedaan aan de hand van een database van 224 prototypen van waterstofauto's die in de afgelopen 40 jaar ontwikkeld zijn. In deze prototypes zijn de keuzes zichtbaar die de autofabrikanten in de loop der jaren gemaakt hebben. De analyse bevestigd dat er daadwerkelijk sprake is van variatie en selectie binnen de industrie, dat bedrijven verschillende voorkeuren hebben voor configuraties van componenten, maar dat er desondanks een dominant ontwerp is voortgekomen uit deze fase. Dit ontwerp bevat een PEM brandstofcel voor de conversie van waterstof in elektriciteit en maakt gebruik van gasvormige waterstofopslag onder hoge druk. In plaats van reguliere marktcriteria is er sprake van selectie op basis van feitelijke en verwachtte prestatiekarakteristieken, verwachtte regelgeving en strategisch manoeuvreren door de fabrikanten. De verschillende factoren versterken elkaar doordat de fabrikanten allemaal beseffen dat het meest gebruikte ontwerp in deze fase waarschijnlijk ook in de latere marktfase schaalvoordelen zal kennen. Dit is met name te verwachten met betrekking tot de opbouw van een waterstofinfrastructuur die al dan niet compatibel is met de verschillende opslagsystemen in de auto's. Daarnaast geven de meest actieve en leidende fabrikanten ook de sterkste signalen af met hun grote aantallen prototypes, soms in de vorm van kleine series. De overige bedrijven die zich meer als volger gedragen conformeren zich aan de ontwerpkeuzes van de leiders. Dit gedrag bevestigd het vermoeden dat prototypes in de auto-industrie meer zijn dan testobjecten, ze worden actief ingezet door bedrijven communicatiemiddel, zowel naar consumenten en overheden als naar andere fabrikanten.

In **Hoofdstuk 5** wordt vervolgens onderzocht in hoeverre de convergentie van de prototypeontwerpen, ook terug te vinden is in de patentportfolio's van de autofabrikanten. De veronderstelling was namelijk dat de technologieën die toegepast zijn in de prototypes ook gepatenteerd zijn door dezelfde fabrikanten. De trend richting de PEM brandstofcel en gasvormige opslag zou dus ook in de patentportfolio's zichtbaar moeten zijn. Echter, dit is alleen het geval voor de brandstofcel. Voor waterstofopslag is er juist sprake van divergentie in de portfolio's: meer en meer verschillende technologieën worden gepatenteerd. Hiervoor zijn verschillende verklaringen denkbaar, maar het roept in elk geval de vraag op in hoeverre er op korte termijn sprake zal zijn van commercialisering van waterstofauto's aangezien de fabrikanten nog geen duidelijke voorkeur voor een opslagsysteem hebben ontwikkeld. Ook voor de opbouw van een waterstofinfrastructuur is dit problematisch, want verschillende opslagmethoden vragen om verschillende tanksystemen. Zolang deze competitie nog voortduurt, is het dus raadzaam om een zo open mogelijke infrastructuur op te bouwen.

In **Hoofdstuk 6** wordt de vraag gesteld waarom sommige technologische verwachtingen wel en andere niet als geloofwaardig beschouwd worden. Hierbij wordt het verwachtingenwerk zowel op het componentniveau als op het systeemniveau bestudeerd. Meer specifiek is het waterstofprogramma van het Amerikaanse Ministerie van Energie onderwerp van studie. Dit programma en haar deelnemers vervullen een dubbele rol, zowel die van enactor en als van selector. Op basis van beleidsdocumenten, notulen van vergaderingen en korte interviews met stafleden van het ministerie wordt onderzocht hoe verwachtingen beoordeeld worden vanuit beide rollen.
Technologische verwachtingen zijn geloofwaardig, zowel volgens enactors als selectors, wanneer ze gebaseerd zijn op vooruitgang die geboekt is in het verleden, wanneer er een pad geschetst kan worden waarlangs verdere verbetering nog mogelijk is en wanneer hiermee een doelstelling, op tijd, bereikt kan worden. Dit einddoel moet ook corresponderen met een zekere (maatschappelijke) behoefte. Al deze elementen kunnen uiteraard ook onderwerp van discussie zijn en enactors van concurrerende opties zullen elkaars verwachtingen in twijfel trekken. In een hiërarchie van systemen met onderliggende componenten wordt het systeem geloofwaardiger geacht wanneer de componenten beloftevol zijn en vice versa. In het hoofdstuk wordt ook getoond dat de toenemende druk op de waterstofvisie, als gevolg van tegenvallende resultaten, heeft geleid tot striktere selectie van componenten. Met andere woorden, de zwakkere opties worden afgedankt om de geloofwaardigheid van het systeem te redden.

De afname in interesse voor de waterstofauto kan niet los gezien worden van de recente terugkeer van de batterij-elektrische auto. In **Hoofdstuk 7** wordt dan ook deze competitie op systeemniveau onderzocht. Conceptueel wordt gebruik gemaakt van het begrip 'technologische niche' dat inzichtelijk maakt hoe radicale innovatie kan plaatsvinden ondanks sterke tegenkrachten vanuit de bestaande praktijk. De niche namelijk, vormt een beschermde omgeving waarbinnen de nieuwe technologie kan rijpen en waarin de betrokken actoren kunnen leren over werking en toepassing in een praktische context. De meeste studies waarin het begrip technologische niche centraal staat, beschrijven de ontwikkeling van een enkel innovatietraject. In dit hoofdstuk wordt getracht om met behulp van dit perspectief de competitie tussen verschillende trajecten inzichtelijk te maken. De waterstof- en de batterij-elektrische auto worden beide beschermd door zowel bedrijven als overheden. Dit gebeurt vanuit de breed gedeelde overtuiging dat er een 'auto van de toekomst' ontwikkeld moet worden. Deze gedeelde beschermde ruimte maakt echter wel dat beide onderling strijden om dezelfde middelen, gunstige regelgeving en de initiële opbouw van een infrastructuur. In dit hoofdstuk wordt deze competitie gereconstrueerd aan de hand van verschillende ontwerpen die gehanteerd worden binnen de beide trajecten en de verwachtingen die geuit worden ten aanzien van de trajecten. De veronderstelling is namelijk dat binnen de niche geleerd wordt over verschillende ontwerpopties en dat hieruit een optimaal, en beloftevol, ontwerp voortkomt. Het onderzoek toont aan dat de aandacht voor beide trajecten telkens verschuift, van batterij-elektrisch in de beginjaren '90, naar waterstof vanaf 1998 en weer terug naar batterij-elektrisch vanaf grofweg 2008. Deze verschuivingen op globaal niveau worden ingegeven door teleurstelling rondom de ene optie en nieuwe hoge verwachtingen van de andere. Terwijl er op lokaal niveau nog wel ruimte is voor beide opties tegelijkertijd, lijkt het er op dat op meer globaal niveau slechts ruimte is voor een van beiden.

De oorzaak van de recente teleurstelling rondom waterstofauto's en de afnemende interesse zijn dus deels het gevolg van sterke beloften rondom de batterij-elektrische auto. Maar, zo wordt betoogd in **Hoofdstuk 8**, ook de waterstofgemeenschap zelf draagt hiervoor verantwoordelijkheid. Aan de hand van de prototypes en uitspraken van de auto-industrie wordt getoond hoe verschillende autofabrikanten overdreven verwachtingen hebben geschapen en zo mede vormgegeven hebben aan de waterstofhype. In het bijzonder hun uitspraken over commercialisering van waterstofauto's, vanaf de millenniumwisseling zou dit het geval zijn, zijn veel te optimistisch gebleken. Daarbij heeft de industrie ook een dubbel repertoire van uitspraken gehanteerd. Enerzijds een repertoire van zeer optimistische uitspraken en anderzijds, en pas later, veel bescheidener uitspraken waarin ook de meer problematische aspecten van de waterstofauto benadrukt worden. Het is aannemelijk dat de industrie het type uitspraken gebruikt dat het beste van pas komt op enig moment. Enerzijds om te benadrukken dat ze druk doende zijn met de ontwikkeling van de 'auto van de toekomst' en daarbij ook om steun te vragen en anderzijds om te voorkomen dat overheden de emissieregels aanscherpen in de verwachting dat emissievrije auto's al marktrijp zijn. Met het overwaaien van de waterstofhype komt een deel van de ontwikkelingen stil te liggen. Meer gebalanceerde verwachtingen hadden wellicht tot een meer gelijkmatig innovatietraject kunnen leiden. Voor beleidsmakers ligt hier dan ook een uitdaging, om niet mee te gaan in de hypes en teleurstellingen die passeren.

In het afsluitende hoofdstuk worden de bevindingen van de zeven empirische hoofdstukken samengebracht. Ten eerste wordt het begrip 'arena's van verwachtingen' verder uitgewerkt. De arena's worden gedefinieerd als sociaal-cognitieve ruimten waarin een brede waaier van verwachtingen en inschattingen van verschillende actoren samenkomen en waarin ook eerdere verwachtingen een grote rol spelen. De arena's kunnen op verschillende niveaus gedefinieerd worden. In de arena voor waterstofopslag bijvoorbeeld, vindt de strijd plaats tussen de verschillende opslagsystemen en in de arena voor de 'auto van de toekomst' strijden de waterstof- en de batterij-elektrische auto om ondersteuning. Verder is het duidelijk geworden dat de posities van enactors en selectors niet vaststaan en dat er sprake is van rollen die actoren, afhankelijk van een specifieke context, kunnen spelen. Dat wil zeggen dat een actor bijvoorbeeld eerst als selector optreedt, en vervolgens de geselecteerde optie zal 'enacten' om steun te vergaren voor de verdere ontwikkeling ervan. En, zoals getoond in de casus over de het Amerikaanse waterstofprogramma, het kan ook zo zijn dat binnen een technologische hiërarchie de actoren die het systeem als geheel vertegenwoordigen, en daarvoor dus als enactor optreden, tegelijkertijd keuzes moeten maken ten aanzien van de componenttechnologieën die al dan niet onderdeel 'mogen' zijn van het systeem.

Ten aanzien van de eerste subvraag over de rol van enactors worden drie conclusies getrokken. Ten eerste, het verwachtingenwerk van een gemeenschap van enactors is niet beperkt tot de eigen optie alleen. Naast het scheppen van verwachtingen ten aanzien daarvan, blijkt dat ze veelvuldig benadrukken dat de concurrerende opties niet of weinig beloftevol zijn. Ten tweede, de enactors zijn zich tegelijkertijd nadrukkelijk bewust van de risico's van te hoge verwachtingen. Zij beseffen dat deze kunnen leiden tot teleurstelling bij de selectors en dat dit op de lange termijn ook gevolgen kan hebben voor de ondersteuning van hun optie. Een van de strategieën die zij hanteren om dit risico te beperken bestaat er uit geen kwantitatieve beloften te doen. Deze zijn namelijk eenvoudiger te controleren en te falsifiëren dan kwalitatieve uitspraken. En ten derde, in tijden van lage verwachtingen, bijvoorbeeld nadat een hype voorbij is, zullen de enactors eerder de mogelijkheden en beloften op korte termijn benadrukken dan te vertrouwen op meer speculatieve lange termijn verwachtingen. Daarmee anticiperen zij op de veranderde selectiecriteria van de selectors.

Ten aanzien van de tweede subvraag wordt geconcludeerd dat de selectors een portfolioaanpak hanteren met meerdere opties die zij als beloftevol beschouwen. De belangrijkste criteria bij het beoordelen van technologische verwachtingen zijn respectievelijk de vooruitgang van de opties in het recente verleden, de argumenten voor mogelijkheden voor verdere verbetering van prestaties en verlaging van de kosten en de vraag in hoeverre de opties aansluiten bij de gestelde doelen van de selectors. De opties die niet aan deze criteria voldoen worden uit de portfolio verwijderd. Met andere woorden, technologieselectie draait dus niet zozeer om het kiezen van winnaars, maar eerder om het aanwijzen van de verliezers.

De rollen van enactor en selector staan met elkaar in verband en hetzelfde geldt dus voor het scheppen van verwachtingen en het beoordelen ervan. Een van de hoofdbevindingen in deze thesis is dan ook dat selectors hun portfolio zullen vernauwen op het moment dat zij zelf onder druk staan. Enerzijds doen zij dat omdat hun budget afneemt, en zij dus minder opties kunnen steunen, maar ook omdat een brede waaier van opties het signaal afgeeft dat geen van de opties echt overtuigend is. Bovendien is het zo dat elke verwachting die wordt uitgesproken tegelijkertijd ook een bewering is over het gebrek aan huidige prestaties.

In het laatste hoofdstuk wordt ook een aantal bijdragen van deze thesis aan de innovatiewetenschappen besproken. Ten eerste, aan de sociologie van verwachtingen wordt een beter begrip van de rol van actoren in het ontstaan van collectieve verwachtingen bijgedragen. Dit geldt bij uitstek voor de rol van de selectors, zij maken ten slotte onderscheid tussen geloofwaardige en de minder geloofwaardige verwachtingen. Daarnaast is een aantal kwantificeringen van verwachtingen voorgesteld als aanvulling op de literatuur die hoofdzakelijk van kwalitatieve aard is. In deze thesis is beargumenteerd dat verwachtingen, in het kader van concurrerende technologieën, gemeten kunnen worden aan de hand van patenten, prototypes en uitspraken van wetenschappers en autofabrikanten.

De literatuur op het gebied van concurrerende technologieën is voornamelijk gericht op concurrentie in de markt. Daarmee gaat het voorbij aan de competitie die plaatsvindt in de ontwikkelingsfase en de criteria die dan een doorslaggevend zijn. In afwezigheid van marktcriteria is het vooral een combinatie van actuele en verwachtte prestatiekarakteristieken, verwachtte regelgeving en strategisch manoeuvreren van bedrijven die de selectie sturen in deze fase.

Over de literatuur in het veld van sociotechnische transities kan gezegd worden dat een echt begrip van concurrerende transitiepaden nog ontbreekt. De competitie tussen waterstof- en batterij-elektrische auto's laat duidelijk zien dat zulke paden, of trajecten, met elkaar kunnen concurreren en dat teleurstelling met betrekking tot het ene pad, ruimte kan bieden aan het andere pad. Dit kan leiden tot zeer onregelmatige ontwikkelingstrajecten waarbij dit hollen en stilstaan ook kan leiden tot onnodig hoge (maatschappelijke) kosten en vertraagde innovatie. Ook is getoond dat technologische convergentie niet noodzakelijk leidt tot hoge collectieve verwachtingen. Dat wil zeggen dat een gedeelde visie vaak maar van tijdelijke aard is en dat deze niet per definitie een gunstige uitwerking heeft op het transitietraject.

Op basis van de bevindingen in deze thesis is ook een aantal aanbevelingen geformuleerd voor zowel enactors als selectors. Ook al is het moeilijk vast te stellen welke invloed hype en teleurstelling precies gehad hebben op de ontwikkeling van de waterstofauto, is het de moeite waard om na te gaan in hoeverre 'management van verwachtingen' mogelijk is om meer evenwichtige innovatietrajecten te realiseren. Ten eerste, enactors zouden meer bescheiden verwachtingen kunnen scheppen om zo een hype en daarop volgende teleurstelling te voorkomen. Maar, net zoals in het speltheoretische dilemma 'tragedie van de meent' is het niet te verwachten dat individuele actoren hieraan gehoor zullen geven. Elke enactor heeft een ten slotte individuele prikkel om hoge verwachtingen te scheppen, namelijk om (financiële) steun te vergaren. De gevolgen van de teleurstelling zullen echter weerslag hebben op de gehele gemeenschap en niet zozeer op het 'hypende' individu. Daarom wordt voorgesteld dat het vooral aan de selectors is om niet zonder meer de hypes te volgen. De meest voor de hand liggende manier om dit te bereiken is door beleid te voeren dat weliswaar uitnodigt, of zelfs dwingt, tot innovatie, maar geen technologiespecifieke keuze inhoudt. Het Californische voorbeeld van de niet-technologiespecifieke eis aan autofabrikanten om schone auto's op de markt te brengen is ook daarom nog steeds waardevol. Hetzelfde geldt voor het EU beleid waarin steeds strengere emissieregels worden gesteld.

Afsluitend kan gesteld worden dat de waterstofauto meer dan eens door fases van hype en teleurstelling heen is gegaan en ondanks de verklaringen van sommigen dat de waterstof auto nu dood zo zijn, zou het getuigen van onderschatting van de weerbarstigheid van de waterstofvisie en haar ontwikkelaars om deze optie nu volledig af te danken.

Dankwoord

Hoge verwachtingen en de onvermijdelijke teleurstelling die er op volgt. Het voorlopige lot van de waterstofauto is mij gelukkig bespaard gebleven. Natuurlijk zijn er pieken en dalen geweest in de afgelopen vier jaar, maar dankzij mijzelf, en de mensen die ik hier wil noemen, zijn deze altijd bescheiden gebleven.
Harro, als dagelijks begeleider en uiteindelijk ook als promotor heb je met je scherpe en vaak ook creatieve bijdragen een grote rol gespeeld in mijn ontwikkeling als onderzoeker en waarschijnlijk ook als mens. Ernst, je bent pas in de laatste fase betrokken geraakt bij het project en juist daarom wil ik je hartelijk bedanken voor je commentaren, je enthousiasme en je bereidwilligheid om op zo'n korte termijn in te stappen. Marius, jouw oprechte gedrevenheid en de daaruit voortvloeiende commentaren en bijdragen heeft mijn werk en dit proefschrift zonder twijfel naar een hoger niveau getild.

Als promovendus is het bijzonder prettig om te kunnen werken in een omgeving die tegelijkertijd stimulerend en veilig is. Ruud en Marko hebben de innovatiestudies groep zo vorm gegeven dat jonge onderzoekers niet alleen de kans krijgen zichzelf te ontwikkelen, maar bovendien ook serieus genomen worden als volwaardige leden van de groep.
Van de aio's in de innovatiestudies groep heb ik mij de laatste van de eerste generatie gevoeld en tegelijkertijd de eerste van de tweede generatie. Daarbij ben ik gelukkig nooit tussen wal en schip geraakt en heb ik veel geleerd van de eerste, en stiekem genoten van de worstelingen van de tweede generatie. Een aantal van hen wil ik er graag uitlichten. Op de eerste plaats bedank ik Laurens, als kamer- en lotgenoot van het eerste uur, voor de leuke en stimulerende discussies en ook vanwege de motiverende werking die uitging van jouw successen! Ik word altijd blij van mensen met een dwarse kijk op het leven en Roald jij hebt dit als geen ander. Jouw kamer was daarom een favoriete plek voor de eerste kop koffie van de dag. Wouter, Klaas en Frank, ook jullie hebben wat mij betreft echt jullie karakters laten gelden en het nodige leven in de brouwerij gebracht.

Tijdens de afgelopen vier jaar heb ik met veel plezier een aantal studenten begeleid bij het schrijven van hun scripties. Van het materiaal van een aantal van hen heb ik bovendien dankbaar gebruik kunnen maken. Ik wil daarom ook in het bijzonder Wouter Grooten, Remko Engels, Floris Prager, Maurice Oost en Paul Hagen bedanken voor de prettige samenwerking en hun bijdragen aan het onderzoek.

Van de vele contacten die zijn ontstaan tijdens conferenties en workshops wil ik graag Marloes Dignum en Björn Budde bedanken voor de gedeelde ervaringen van jonge onderzoekers, aan het worstelen met verwachtingen en waterstof. Ook heb ik genoten van de prettige sfeer en het contact met de aio's tijdens de WTMC workshops en summerschools, onder bezielende leiding van Sally, Els en Willem.

Bij het bestuderen van innovatieprocessen ben je afhankelijk van de daadwerkelijke innovatoren voor hun medewerking en de informatie die ze willen verstrekken. Ik wil dan ook mijn waardering uitspreken voor de openheid waarmee de geïnterviewden mij te woord wilden staan. Bovendien wil ik graag mijn bewondering uitspreken voor de gehele waterstofgemeenschap. Dit zijn tenslotte de helden van het verhaal en degenen die de visie, de durf en het vermogen hebben getoond om radicaal te innoveren.

Het scheiden van privé en zakelijk is wat mij betreft zinloos als je van je hobby je werk hebt kunnen maken. Daarom wil ook graag Joyca, Sander, Judith en Ben bedanken voor de meer dan leuke tijd in Maastricht en de springplank die jullie boden voor mijn vertrek richting Utrecht. Met de mannen van het VriendenWeekend wil ik bedanken voor de regelmatig terugkerende hoogtepuntjes van het jaar en ik spreek de hoop uit dat we dit nog lang volhouden.
Mijn ouders, Hanni en Rien, en mijn broer Niels wil ik oprecht bedanken voor het bieden van een veilige en stimulerende thuisbasis. Een kritische geest is noodzakelijk voor het doen van onderzoek en het schrijven van een proefschrift. Ik ben er zeker van dat de mijne van jullie afkomstig is.
Simona, ik zou graag heel zwaarmoedig zeggen dat jij mij door allerlei moeilijke momenten heen hebt gesleept, maar sinds wij samen zijn heb ik geen enkel moeilijk moment meer gehad! Daarvoor en voor nog veel meer verdien je alle lof. Bij dezen. Met liefde.

Curriculum Vitae

Sjoerd Bakker was born in Amsterdam and attended the Alkwin Kollege in Uithoorn. In 1995 he moved to Enschede to study Chemical Engineering at the University of Twente. The Philosophy of Science, Technology and Society program offered an opportunity to combine engineering knowledge with a broader understanding of the role of science and technology in society. In 2003 he graduated with a Master's thesis on the development of telemedicine networks for medical specialists.

Before joining the Innovation Studies group at Utrecht University, Sjoerd held research positions at the University of Twente, Maastricht University and the European Centre for Digital Communication (EC/DC) in Heerlen.

Sjoerd is currently a post-doc researcher at the OTB Research Institute for the Built Environment and works on an NWO funded project on the feasibility and impact of the transition to electric mobility in the Randstad.

Publications

Bakker, S. (2011) Hydrogen: a stack of competing visions, Book chapter in "*What is Sustainable Technology? Perceptions, Paradoxes and Possibilities*", eds. K. Mulder, D., Ferrer-Balas & H. van Lente, Greenleaf Publishing, Sheffield

Bakker, S., van Lente, H. & Meeus, M. (2011) Arenas of Expectations for Hydrogen Technologies, *Technological Forecasting & Social Change*, vol.78, no.1, 152-162

Bakker, S. (2010) The car industry and the blow-out of the hydrogen hype, *Energy Policy*, vol.38, no.11, 6540-6544

Bakker, S. (2010) Hydrogen patent portfolios in the automotive industry - The search for promising storage methods, *International Journal of Hydrogen Energy*, vol.35, no. 13, 6784-6793

van Lente, H. & Bakker, S. (2010) Competing expectations: the case of hydrogen storage technologies, *Technology Analysis & Strategic Management*, vol.22, no.6, 693-709

Bakker, S. (2007) Op zoek naar de juiste bron, *Milieu*, Jaargang 13, nr.4