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Arenas of Expectations for Hydrogen Technologies

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Abstract

Technological options can be regarded as variations in an evolutionary development process. The variations are put forward by their respective technological communities and are selected by technology selectors. Building on the notion of quasi-evolutionary technology development we show how technological communities secure their position on R&D agendas through feeding and maintaining expectations in arenas of expectations. We examine this process by studying the expectations work of the community that tries to develop metal hydrides for the on-board storage of hydrogen for mobile applications. Metal hydrides are proposed as a promising alternative to gaseous and liquid hydrogen storage but are yet underdeveloped. Its proponents however, succeed in convincing their sponsors of the future potential of metal hydrides. In this paper we show how expectations of this technological option are raised and maintained by its developers and how this has kept them on hydrogen technology agendas for over 40 years.

Keywords: alternative fuel, energy storage, hydrogen, mobility, on-board

1 Introduction

While car manufacturers are working on the commercialization 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. Clearly, some of these technologies will be successful, other will fail. This raises questions about how engineers, firms and policy makers deal with the uncertainties of hydrogen futures. On the one hand, scientists and engineers try to make sure that ‘their technology’ is given the chance to be developed further. They do this by explaining to outsiders why their technology can deal better with the challenges ahead than any of the other competing solutions. In other words: these scientist and engineers have to raise expectations of their technology to get the backing they need from their sponsors. On the other hand, proponents of one hydrogen option will also need the success of other parts of hydrogen systems and of the idea of ‘hydrogen economy’ as a whole. The expectations of the various efforts are linked, therefore, and compete and reinforce each other at the same time. To study the dynamics of chained expectations in more detail, we have performed a case study on one of the hydrogen technological communities. This technological community proposes to store hydrogen in the atomic lattices of metal alloys; *metal hydrides*. If their work is successful, larger quantities of hydrogen can be stored on board a vehicle, thereby enlarging the cars driving distance without refuelling. So far however, metal hydrides researchers have not found what they are looking for. But still, they can continue their work as long as their sponsors have high enough expectations of their quest for better alloys and catalysts.

To study the expectations work of this community, we develop a framework in which we bring together theoretical findings about technological expectations, (quasi-)evolutionary innovation and technological communities. At the centre of this framework are *arenas* of expectations where ‘enactors’, i.e. communities developing technologies feed and test the future outlooks of a technology vis-à-vis the concerns and hopes of technology ‘selectors’. In this paper, we start off with an introduction into the role of expectations in technology development. This is then placed in the context of evolutionary technology development and the role therein of competing technological communities. When the framework is applied to the case of metal hydrides for hydrogen storage (section 3) we are able to trace and explain the way chained expectations shape developments in hydrogen research and development.

2 Chained Expectations of Hydrogen Technologies

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 technological innovation was introduced by Van Lente (1993) in the field of Science and Technology Studies, and developed into a ‘sociology of expectations’ (Brown and Michael 2003). This work shows how promises and expectations of technology are part of the 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 shared between actors in different communities or different levels of technology development (Borup et al. 2006). When we use the sociology of expectations perspective to analyse expectations and their role in hydrogen visions we can see both attempts to stimulate technological development as well as efforts to coordinate action.

In hydrogen vision reports (Department of Energy 2002; Duwe 2003; HFP 2005; European Commission 2006; Marshall 2006; Vermeulen 2006) a number of differing visions are explicated (McDowall and Eames 2006). These visions aim mainly at mobilizing 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, amongst 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.

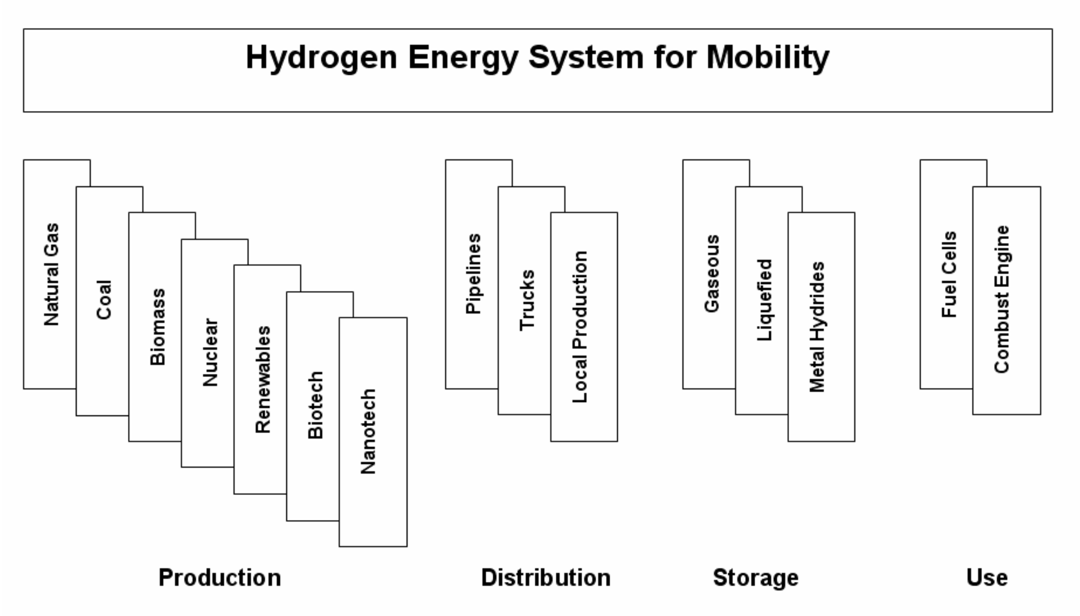

Figure 1: The prospective chain of hydrogen energy technologies

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 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. It is not in existence yet but it is a projection of things that could come into being and it is therefore prospective. In all hydrogen visions this prospective chain, or varieties of it, is filled in with promising technologies. The prospective chain and its suggested component (technological) options are shown in Figure 1. Despite the fact that none of these technologies is ready, hydrogen visions have to build upon them for their credibility. This implies that hydrogen visionaries and proponents need to create and maintain expectations of component technologies to some extend when they defend a hydrogen energy system or even a 'hydrogen economy'. The chain of technologies is thus also a chain of positive expectations. The viability of singular hydrogen technologies depends upon support for the hydrogen vision as a whole, while the hydrogen vision, in its turn, is dependent upon expectations about individual components.

2.1 Quasi-Evolutionary Technology Development

Technological development or innovation is often described as a continuing evolutionary process of variation and selection (Nelson and Winter 1977). Here, different technologies are the variations, while the market, in a broad sense, is their selection environment. Successful innovations are therefore assumed to be the fittest in its given market. Limited and finite resources on the part of the selection environment, or selecting actors and organizations, call for choices to be made between different technological options. This happens on the level of technological systems, but just as much on the level of individual technological solutions. This creates competition, not only between the systems and solutions, but also between the actors advancing them.

In addition to this, the *quasi*-evolutionary model (Van den Belt and Rip 1987; Schot 1992; Rip et al. 1995) stresses the role of anticipation by actors. Evolution is only quasi, because variations are not blind and selection is not independent from variations. Actors anticipate on the selection environment because they have some understanding of its future demands. They do this for instance by taking the performance of current cars as a benchmark and by extrapolating ongoing improvements. Actors will also seek to modify selection environments, by voicing expectations or with other moves like forging strategic alliances. The evolutionary development is therefore said to be embedded in a "*cultural matrix of expectations*". This provides us with a model of technological development and competition that is less dependent on spontaneous variation, but instead relies on guided search, through different heuristics, by actors.

An interesting elaboration of the quasi-evolutionary model comes from Garud and Ahlstrom (1997) who have shown that a socio-cognitive 'game' is played between, on the one hand, actors that enable technological development ('enactors' in their phrasing) and, on the other hand, actors that select the technologies they think are best at meeting their demands ('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.

On both sides, criteria are used to assess variations, both ex-ante and ex-post. These criteria however are not necessarily stable and shared by all actors, as many studies of technology have shown (Bijker 1995). 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. In practice, this means that enactors will stress the criteria their solution fits best with. Technology selectors 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 constructing of needs and selection criteria, as they are by material characteristics (Pinch and Bijker 1984).

Ideally, selectors would like to have the opportunity to judge technological options on the facts, specifications, and actual proof of the usefulness and economics of the solutions. 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 technological systems however, investment decisions (and other pre-selections) have to be taken in an early stage of development. In this stage uncertainty is much bigger 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 laboratory performance and specifications, but far less has been learned about real-life use, system integration, possible learning curves, and economies of scale of different products. Expectations of possible improvements are thus the only basis for decisions to be taken in this phase, for enactors and selectors alike.

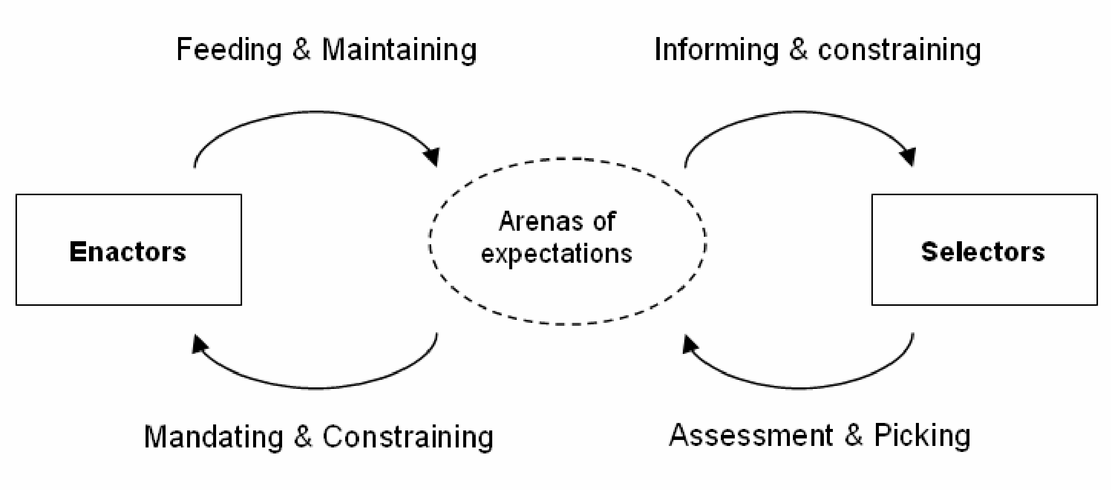

Figure 2: Conceptual model of the quasi-evolutionary enacting-selecting game based on expectations

2.2 Technological communities of enactors

In order to study the dynamics of chained expectations in the enacting and selecting game, one has to look at the actors on both sides. First we will discuss the actors on the enacting side, the developers of component technologies. The selectors will be dealt with shortly at the end of this subsection. In our case study we focus on the expectations work performed by the technological community, the enactors of a technological variation.

As hydrogen technologies are highly complex and systemic in nature, it takes a multitude of actors and organisations to develop the solutions needed. The concept of technological communities (or innovation community (Lynn et al. 1996)) is developed and used in order to deal with just such inter-actor and inter-organizational behaviour in innovation (Rappa and Debackere 1992; Debackere and Rappa 1994; Lynn et al. 1998; Rosenkopf and Tushman 1998). While many have written on this subject, we use the definition provided by Rappa and Debackere. According to them, technological communities are:

> *"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)

This definition is applicable to the sets of actors that work on the different component technologies for the hydrogen energy system. Actors are globally dispersed but have a shared goal in trying to develop solutions to shared problems. And have therefore shared interests 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 and 'their' technologies and their competition with other communities. How these communities use expectations and promises in this competition is not discussed explicitly however. We argue that expectations work, next to technological success, is important to the growth and success of any technological community.

For all hydrogen technologies (See Figure 1), there is a technological community working on the technology itself and its position in the prospective chain. And they all consist of actors throughout science and industry.

From the literature we take two interesting 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. For this paper this is a useful distinction, too, because the enactor community under study here is mainly an academic community. Other enactor communities of hydrogen technologies are much more industry based. This will have an effect on their 'expectations work'. For scientists, positive expectations might be sufficient by themselves, as long as these provide them with a mandate and funding to allow them to continue their research activities. For industry it seems that actually meeting the high expectations is somewhat more vital to the survival of their business.

Secondly because academics are by definition concerned with a specific field of knowledge (their specialism, or 'paradigm') whereas industrial actors might care more about finding any solution than finding their own typical solution. In other words, a dominantly academic community is focused on a specific area of interest that might turn out to be relevant for some kind of problem. An industry dominated community is focused on providing a means to meet a goal, sometimes based on the community's competencies, sometimes regardless of any such rationale. This distinction is made in the literature as a distinction between paradigm-driven and solution-driven communities or as a distinction between design-based and sponsor-based communities (Wade 1995).

All this does not imply that a community is homogeneous by composition. Different actors have different roles within the community. One could expect for instance a hierarchical order from leaders and spokespersons to scientist and engineers that are mainly concerned with the work floor. A community leader, a highly respected professor for instance, is more likely to engage in the actual expectations work than a laboratory analyst. Also, the expectations held within the community might differ from one member to another.

2.3 Technology selectors

On the selection side it is harder to identify groups of actors. The selectors do not share common interests as much as the enactors do. Even though the focus of this paper is on the enactor's side of the game, we discuss here some examples of selectors in the case of hydrogen technologies.

Research councils can be seen as selectors in the science stage of development. Guided by governments they select promising research trajectories and the accompanying proposals. Car companies are selectors, too, and probably enactors at the same time, for the elements storage and use. An example of selection by car companies is the choice of the BMW management to choose a combustion engine over a fuel cell system, probably because of its appeal to the typical BMW customer. One example from literature in which a car manufacturer communicates about its selection process comes from General Motors (von Helmolt and Eberle 2007). They discuss different options and their current state of development in terms of quantifiable criteria such as hydrogen content per unit of volume (for storage options) and cost per unit. For future development they rely on arguments such as learning curves and hopeful new approaches.

The distinction between enactors and selectors is analytically clear, but empirically less straightforward. For example, in the case of research councils it is hard to distinguish between the enactors and the selectors. Research councils are made up of scientists and these scientists are often part of the community itself 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. Yet, the distinction between the two sides of the quasi-evolutionary game is an important analytical distinction, to study and understand the processes that take place.

2.4 Arenas of Expectations

In order to study the hydrogen enacting-selecting game based on expectations, we need one more conceptual ingredient. Expectations are put forward in *arenas*, as we propose to call them. An arena of expectations is a locus where expectations are voiced and tested, where they are confronted with experience, knowledge, and interests. The ongoing processes of variation and selection of systemic technologies are not just bilateral interactions but a collective social process over time engaging a lot of different actors and organizations. The loci for these multi-actor interactions are scientific conferences, journals, wider media, committees, research councils, etcetera. Within arenas of expectations battles of expectations take place, 'trials of strength' (Latour 1987) and are fed with past experiences with comparable technologies, and with facts and forces of the social and economical context. Therefore the accumulation of knowledge and failures, expectations and disappointments, hopes and fears become relevant in arenas. In Figure 2 we summarize how in arenas, expectations are fed and maintained by enactors and used and assessed by selectors.

It shows, on the left side, how 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 because 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 enactor community. The drawback of robust expectations, however, is that they may constrain the enactor community not to deviate from their promising approach.

On the right side of the arenas are the selectors, who are informed (but also constrained) by expectations and who make assessments and pick their winners, in whatever phase of the selection process. As a result, some options are favoured or at least not contested by selectors, others are seen as not viable, or not yet. The results of the selector's decision making process feeds back into the arenas and influence the ongoing struggle for mandate. Note that there may be multiple arenas, at various levels of aggregation. Highly detailed expectations of materials or techniques may be 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' will figure in public debates on sustainable energy.

In order to gain insight in the hydrogen enacting-selecting game and the interactions in the arenas, we studied the expectations work of the technological community that tries to develop metal hydrides for hydrogen storage.

2.5 Methodology

In our case study we analysed various literature sources, such as hydrogen vision reports and technology reports, scientific communication from the community itself. We also did a series of semi-structured interviews 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, are concerned with metal hydrides research. Their projects vary from experimental work on new material compositions, to new production methods and computational modelling of the hydration processes; they cover the main subfields of metal hydride research.

In 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 the selection criteria used by technology selectors.

3 Metal Hydrides

Visions about a future hydrogen energy system can be found in many places, in governmental reports, in engineering circles as well as in the popular press. A favoured way to introduce the future of hydrogen is to use technology roadmaps (Phaal et al. 2004). Typically, hydrogen visions and technology roadmaps mention three basic options for on board storage.

- Liquid storage (LH)
- Gaseous storage (GH)
- Storage in 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).

3.1 The on-board storage problem

The visions and roadmaps seem to agree on what to expect from the three main solutions of hydrogen storage. All have their (fundamental) pros and cons and these figure repeatedly in the reports and other literature, in the same way. From the arenas, the vision reports can be taken as a representation of the debates within the arena, we draw a number of preliminary conclusions.

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[1]). The gas is pressurized up to 700 bar, consuming about 20% of the energy; this results in acceptable volumetric energy densities. Safety concerns and the production costs, however, add to the doubts about this solution. In terms of expectations voiced in the documents, the liquid and gas solutions are not seen as very promising because these drawbacks are seen to be caused by thermodynamic laws. According to these 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 in gas and liquid tank design focuses mainly on cost reduction and safety. 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 to improve. The documents all mention the underdeveloped current state of affairs with metal hydrides but also stress the future potential as, possibly, energy efficient method for storing large quantities of hydrogen without taking up too much space in the vehicle. In other words: the 'Holy Grail' of hydrogen storage might be just around the corner but is not discovered yet.

3.2 The metal hydrides community

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 strongly in the EU countries. In the year 2003 there were three ongoing EU[2]. research programmes, whereas in 2008 five networks existed. The number of institutes involved in this research has risen as well. At the time of this case study six research groups were involved in metal hydrides research in the Netherlands which equals roughly thirty researchers. The 'Sustainable Hydrogen' research program was an important factor in the growth of the Dutch branch of the community. Before the start of this program the community was limited to only two university groups.

3.3 Early years

So far, however, progress has been slow over the years. From the 1960s onwards researchers have shown interest in metal hydrides as means of hydrogen storage. Since then a number of different materials and approaches have been studied. 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). While these hydrides can be used at low temperatures and are thus interesting for on-board application, their drawback is the weight of the base metals used which would result in a very heavy tank-system. Since then the hydrogen to weight of the system ratio has dominated the metal

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[1] 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.

2 This data was collected for an internal report: Oost, M., Netwerken in waterstofopslag' Utrecht University, 2008

hydrides research logic: 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 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. But high-temperature here means that the material only does so at temperatures above 200^{o}C (Güther and Otto 1999). This is not suitable for practical use because this would require active heating of the tank system and this brings down the energy efficiency of the storage system dramatically.

3.4 New hope

A new impulse to the community was generated by Schwickardi & Bogdanovic with their 1997 article which demonstrated the potential of alanates (for instance NaAlH4) when doped with TiO_2 (Bogdanovic and Schwickardi 1997). The titanium oxide catalyst was 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 IJHE and the *Journal of Alloys and Compounds*, in which many of the involved researchers publish their work. Together with the burst in alanates research, a large number of other hydrides were given a chance.

The three main specifications by which the suitability of metal hydrides is measured are the gravimetric density, the operating temperature range and the kinetics of ab- and desorption. Especially 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, 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 because smaller particles have a bigger surface area to weight and shorter distances from the edge to the centre of the medium. Ball milling of material, also used to create less favourable alloy-crystals, 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 wt% than 3-4. 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 9wt.% (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 discovered that scores well on gravimetric density, thermodynamics, and kinetics. The actual performance of metal hydrides (the complex hydrides bar) in 2006 is shown in figure 3. Likewise, the International Energy Agency has 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, metal hydrides have been on research agendas for 40 years and expectations gave researchers their needed mandate but most research lines did not deliver sufficient practical results. The burst of research tracks testifies to the unshaken belief in the future potential for metal hydrides and some metal hydrides are used for stationary purposes or in some niche markets like the German Submarines (Hammerschmidt 2006). But the real promise of low-volume, energy efficient mobile storage has not come true. Therefore, the future of metal hydrides research is uncertain. 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 however, research funding for hydrogen storage is less favourable. For instance, it receives hardly any attention in the Hydrogen Joint Technology Initiative (JTI) proposal, the main EU R&D program for hydrogen for 2008 to 2015. In this public-private partnership the focus is on production, distribution and use (FC's) of hydrogen.

4 The community at work

The question is: how did this research community performed in the enacting-selecting game. How, for instance, did they manage to avoid the backlash of several disappointments? How did they feed and maintained expectations and how did the evolving expectations constrain the directions of the search? We will analyse how expectations were fed to and maintained in the expectations arenas by the metal hydrides community and how this has resulted in a mandate for their work.

4.1 Feeding expectations

The key assumption that underpins the expectations about metal hydrides during the last decades is the idea that gaseous and liquid options are not satisfying solutions to the on-board storage problem. Thermodynamic laws, according to the prevailing arguments, prevent further development in terms of energy efficiency of these methods. The metal hydrides community continuously points to these limitations and presents their option as the problematic but promising alternative. They stress this point in their scientific publications, their contributions to conferences, and their negotiations with research councils. An often cited version of this argument is the Schlapbach & Züttel article in *Nature* (Schlapbach and Zuttel 2001). From the interviews we learned that only one of the scientists was directly involved in the process of shaping the research program he is involved in. The rest claim that their activities in terms of communicating expectations were limited to writing their research proposal. The true feeding of expectations is only done by a small number of informal leaders in the community. In most research proposals, small scale expectations work, expectations are voiced mainly on the outcomes of small knowledge development steps. 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 by no means quantitative. One reason for this is that the scientists prefer to be modest 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)*

They are not sure however how this disappointment would ever 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 expectations of the metal hydrides 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)*

Discussions like these, about the feasibility of metal hydrides as an alternative to liquid and gaseous storage, take place only on conferences and meetings where the wider hydrogen community is present. Only a minority is structurally involved in these debates. For the rest of the community, the most important arena is their own metal hydride arena. This has loci in a number of journals, at specific conferences and network meetings. Here it is often not really necessary to stress the importance and potential of metal hydrides, as long as their own research is promising enough 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, are merely meant to provide some societal relevance for the research than to promote the option of metal hydrides as such.

4.2 Getting a mandate

Since the Bogdanovic article in 1997, the metal hydride community has had no problems with getting funding for their research. The researchers perceive 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. Others feel that ‘*things have only just started*’ and that funding will continue for the foreseeable future.

A general notion amongst them is that research programmes do not last long enough to generate significant results in terms of materials development. This could pose a threat to the field because it is expected to deliver practical solutions within the timeframe of the programmes. Disappointment on the side of the technology selectors could very well be the result of this. An indication is the assessment report on EU funded hydrogen and fuel cells research, which critically reviewed the progress of solid hydrogen storage because its performance is still far from the targets set (European Commission 2008).

As said, the current gaseous storage systems, up to 700 bar, are considered to be the benchmark technology. The researchers acknowledge that metal hydrides at this stage cannot meet this benchmark. This goes even more for the targets set by the DOE, EU and IEA. While they sometimes use these targets to stress the need for further research, the do not agree with them in terms of the actual needs of the car industry. From their contacts with 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 (SUV’s) rather than accepting a different mode of personal transport that would require less hydrogen on board for an acceptable driving range.

The competition between the different storage solutions is viewed differently by researchers that have been in this field for years period than those that have entered more recently. The latter see lots of opportunities for improvement of the materials' performance. 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. Researchers that have been in this field for over 20 years have a much more modest outlook on future improvements. It would require truly groundbreaking results, perhaps from yet unknown alloys, to reach an acceptable level of performance in terms of the capacity, thermodynamics and kinetics. However all agree on the beauty of the metal hydrides concept as being the low volume method for storing hydrogen.

On the competing solutions they agree as well. They share the notion that liquid storage requires too much energy and that the hydrogen losses are probably too big for an automotive solution to be acceptable. For gaseous storage their main arguments rely on the volume and energy required and the safety issues. The do agree however that GH does provide a practical solution, be it not ideal, and is therefore to be considered as the benchmark for hydrogen storage technologies.

4.3 Main findings

In table 1 we have summarized expectations in the two most relevant categories (metal hydrides' progress and the hydrogen storage) that are held either within the hydrides community itself, shared by actors in the wider hydrogen community, or disputed among the hydrogen community. The statements here represent the success of the community in convincing the relative outsiders of their potential for future success and involvement in the hydrogen chain of technologies. Mostly there is some overlap between the hydrides community and the wider hydrogen community. This not really surprising considering the continuous and sizeable support the community receives for its work. However there are somewhat more doubts about the practical outcomes of the research. Given the stage of development there is not a lot of knowledge on the effects of practical use of hydrides and therefore there remain many doubts about the cycleability and cost (the search is mostly about finding a lightweight, high capacity hydride).

Table 1: Shared and disputed expectations on two levels, between the metal hydrides community and the arenas

	Enactors		**Selectors**	
	Feeding & Maintaining (input for arena's)	**Mandating & Constraining (output from arena's)**	**Informing & Constraining (output from arena's)**	**Assessment & Picking (input for arena's)**
Metal Hydrides Progress	- Promising materials - Extrapolation of results - Knowledge leads to performance	- Wide mandate (carte blanche?) - little pressure to deliver - practical results other solutions deemed not satisfying	- MHs have potential - New material can be discovered - Some progress is visible	- Let's try and see - Hope over expectations - Targets and timeline - GH will do for now
Other Storage Methods	- GH and LH will not be improved significantly in terms of capacity and efficiency - DOE norms are too high.	- Industry is working hard on LH and GH - Benchmark set by gaseous - wide set of specifications to meet	- GH and LH are not entirely satisfying	- For now focus on gaseous storage and improve on the related cost and safety issues - 700 bar could be enough and safe

Ideas on the other storage methods are clearly negative within the hydrides community. These methods will not be improved 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, specifically, 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.

As far as system integration goes, this is only a matter of subject within the metal hydrides community when it comes to the transfer of heat from the fuel cell to the hydride tank. This heat can be used to release hydrogen. In other arenas this argument is apparently not relevant, it is all about the weight percentages, filling times and operating temperatures.

The last category of expectations deals with the relation between metal hydrides and hydrogen energy systems. 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. The role of metal hydrides in this is crucial, while this does not seem the case for actors in the wider arenas of hydrogen. Here on board storage is considered an important factor, but not vital to the future of hydrogen. Still, metal hydrides appear to be providing a useful promise for the future of hydrogen to silence the critics. One can state furthermore that there is some dispute about the actual role of these kinds of technological developments for the success of hydrogen. Some believe that outside factors such as the price of oil or very stringent environmental regulation can really support the rise of the hydrogen economy.

5 Conclusions

Metal Hydrides have been on the hydrogen agenda for 40 years. This implies that the community has been successful at feeding and maintaining expectations during this time. They have continuously stressed the future possibilities of metal hydrides and contrasted this with the fundamental barriers faced by liquid and gaseous storage. As a result of their work, some progress was made in the storage capacity of metal hydrides.

In the expectations arenas there seems to be consensus on the issue of limited possibilities for progress for both liquid and gaseous hydrogen storage. Alternatives are therefore welcomed and given a chance to develop. Furthermore, the promise of a near ideal hydrogen storage medium helps in constructing viable visions of hydrogen as the fuel of the future.

Apart from the fact that the competition within the hydrogen storage race has been successful, hydrogen as future energy carrier has maintained its high expectations as well. Due to the high oil-price and ever growing concerns about the changing climate, all alternative energy concepts have drawn quite some attention. The metal hydrides community continues to ride along on this bandwagon.

For the enacting-selecting game we studied, we have shown that feeding expectations is important for the enacting technological community. The exchange or communication of expectations does however not only take place in bilateral and synchronous fashion during bridging events, but also in a more multilateral and asynchronous fashion through scientific articles, future studies, roadmaps etc. The interaction between enactors and selectors results in the selection of a number of technologies. The actors and their expectations and promises meet in different arenas for different aspects of the technology and different levels within the prospective technological system. Being part of the prospective system therefore implies taking part in the relevant arenas of expectations.

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