

Fuelling Chained Expectations in Hydrogen Communities

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Abstract

This paper investigates the dynamics of chains of expectations and focuses on research and technological development within technological communities. Hydrogen is one of the possible energy carriers for mobility in the future. The various hydrogen visions that circulate relate expectations on different levels of technology and society. The visions are highly contested and are accompanied by numerous internal and external uncertainties. We focus on the dynamics of expectations (as substitutes for facts) in the envisioned chain of hydrogen technologies. Expectations, as many studies have shown, are of great importance for the development of technologies as they stimulate, steer and coordinate action of actors.

Numerous communities are currently working on the development of separate technological elements that persistently appear as a logical chain in most hydrogen visions: production, distribution, storage and utilization of hydrogen. This raises the question how the chain of expectations is constructed and maintained. In this paper we unravel the following four types of expectations in technological communities:

- 1. Expectations about their own research, design and specifications*
- 2. Expectations about other communities working on other solutions*
- 3. Expectations about the integration of different elements in the hydrogen chain*
- 4. Expectations about broader factors influencing the development and success of hydrogen as energy carrier*

We conclude that the success of different communities and the hydrogen vision as a whole depend on the successful communication of expectations on all of these four levels. Technological communities strive for a favourable position in the prospective chain of technologies, and also have to fuel the chained visions of the hydrogen economy.

Introduction

Hydrogen is one of the possible energy carriers for mobility in the future. The future is in need of an alternative for the fuels used today and this need creates an arena for competing solutions. Hydrogen is one of these possible solutions and has been around for some four decades. Its major appeal is in its versatility and environmental friendliness. There are some drawbacks however that need to be resolved in order for hydrogen to be successful. To do so, a lot of efforts are made to develop technology and create societal acceptance for hydrogen. All of this is done and financed based on actors' expectations of hydrogen technologies. This paper investigates the dynamics of these expectations in the development of

hydrogen technologies and the role that technological communities play in this dynamics. We will show that hydrogen expectations are chainlike configurations of expectations of the different elements needed to make hydrogen technologies work.

The Hydrogen Visions

The various hydrogen visions that circulate explicitly or implicitly relate expectations on different levels of technology and society. This can be the level of visions in which the whole of society is taken into account and in which hydrogen is not just the replacement for fossil fuels but also the fuel for enormous societal changes (Rifkin 2002). Other visions of the future are more down to earth and focus on the development of certain technologies and routes for societal uptake of hydrogen (Ogden 1999). Even though the visions relate to different levels, there's a common framework that they use as a starting point. This framework is visualized in figure 1. At the centre is the notion of hydrogen as substantial part of the energy system; the hydrogen economy. Although the notion of a hydrogen economy is poorly defined, it is used throughout the hydrogen literature.

The major driver for any hydrogen vision is the need for an alternative to (the limited supplies of) fossil fuels. While the driver may seem overly clear, hydrogen visions are nonetheless extremely complex constructions of diverse expectations. This is caused by the system-character of the energy networks, the enormous economical and political interests and the interdependence of different, themselves problematic technologies. This makes that both extremely optimistic, even naïve, visionaries (Rifkin 2002) as well as criticasters (Romm 2004) can write bestsellers with completely opposing conclusions.

Hydrogen 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 two, linked by hydrogen, was the seed for the vision. Added inspiration was drawn from the necessity of finding a replacement for fossil fuels. This two-sided development of the vision can be framed as a *bottom-up push* for the application of new technologies (nuclear and fuel cells) and a *top-down pull* for a regime change (replacement of fossil fuels).

For hydrogen energy systems to function, more is needed than just electricity and fuel cells. A number of enabling technologies, such as storage and distribution, were recognized as being important for the feasibility of hydrogen energy systems. These became part of the vision. Apart from its main inspiration, hydrogen visions are supported by a number of other 'leitbilder' such as the climate issue and democracy as by product of distributed energy systems (Eames et al. 2006).

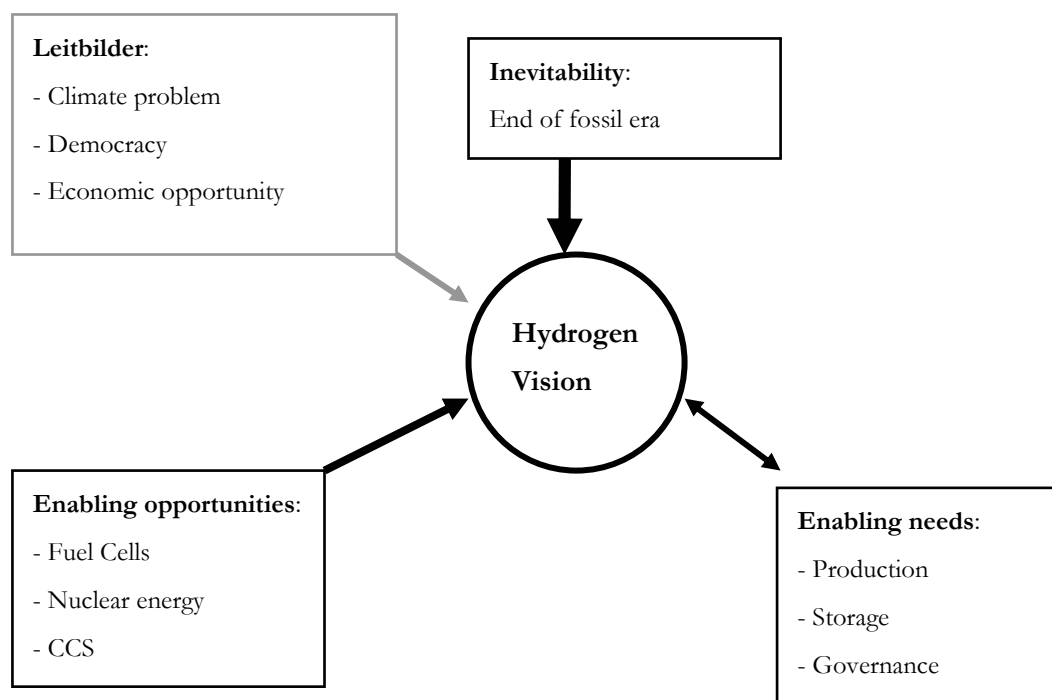


Figure 1: Outline of the Hydrogen Vision

Expectations in Science and Technology Studies

While much attention is given to the readily visible encompassing hydrogen futures, we will focus on the dynamics of expectations within technological communities in the envisioned chain of hydrogen technologies. Expectations, as many studies have shown, are of great importance for the development of technologies as they stimulate, steer and coordinate action of actors. The concept of expectations as key driver for technological innovation was introduced by Van Lente (Van Lente 1993). This work shows how promises and expectations of technology are part of the agenda setting process and thereby help to create a mandate for engineers and other actors. This mandate, very often in terms of funding, gives them the opportunity to continue the development of ‘their’ technology. A mandate comes with requirements that should be met; expectations and promises lead to requirements. Steering and coordination of action is done through the communication of expectations as well. Coordination can be achieved when expectations are shared between actors in different communities or different levels of technology development; horizontal and vertical coordination (Borup et al. 2006).

When we use this perspective to interpret expectations and their role in hydrogen visions we can see both attempts to stimulate technological development and efforts to coordinate action. In hydrogen energy reports a number of visions are described. These visions aim mainly at mobilizing support for hydrogen technologies on the whole. At this system level, hydrogen is in competition with batteries and biomass to become the energy carrier for mobility in the future. If these reports succeed in their mission, aiding to chances for the ‘hydrogen economy’, is hard to judge for now. It’s interesting to see however that apart from the main goal of promoting hydrogen technologies, another issue is addressed as well. This is the issue of what a hydrogen energy system should actually look like in the future. Here expectations play a role in the same manner as on the system level, it is about getting actors to think along the same lines so that they will act in a more coordinated manner.

These reports, as we will show later in more detail, focus on the question what the most probably outcome will be. These reports can be characterised as technologically deterministic, i.e. these reports consider technological ‘qualities’ to be the deciding factor when it comes to selecting the best system configuration. In the expectations literature in STS the focus lies moreover on the role of expectations in this process.

The claim of this body of literature is that it is not only the technological ‘facts’ that matter, but also the way in which actors try to convince other actors of the truthfulness of their ‘facts’. As Garud (Garud and Ahlstrom 1997) has shown, a ‘game’ is played by actors that enable technological development and actors that select the technologies that they think are best at meeting their demands. This game can be seen as part of the (quasi-)evolutionary model for technological innovation. The enabling actors create and put forward technological variations that they claim to be solutions to perceived problems. Actors on the selector side select technologies based on their perception of the problem and their expectations of the solution offered. Ideally, selecting actors 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 reality however, investment decisions and so forth have to be taken in the early stage of development. In this stage uncertainty is much bigger and actors have to make decisions based on expectations rather than facts. In the case of hydrogen technologies numerous aspects are very uncertain. In some niche markets commercial applications are used already, but for mobility purposes however the first commercially viable hydrogen car has yet to be built. Even though a lot is known on laboratory specifications, far less is certain on real-life use, system integration, possible learning curves, and economies of scale of different products. Expectations of possible improvements are thus the basis for decisions taken in this phase. And it is therefore not so much of interest to this paper whether expectations of hydrogen technologies are realistic or not. It is of interest how expectations of hydrogen technologies are vital to the success of actors on the variation side, i.e. technological communities.

In the following sections we will try to show how these actors deal with these uncertainties and how they try to convince actors on the selection side of the expected outcomes of their work. First we will systematically study a number of policy reports that describe possible futures for hydrogen technologies and its introduction into society. This provides us with a starting point for unravelling the diverse expectations on different levels of the hydrogen vision that give shape to the context of the game.

Collective Causal Map

In order to analyze policy reports on hydrogen energy we used a causal mapping technique. A causal map is a map of some persons’ ideas about the causal relations between different elements. Originally, causal mapping was used as a tool to analyze managers’ decision making processes. It is therefore strongly related to the concept of managers’ dominant logic (Prahalad and Bettis 2000). This concept demonstrates that some managers are reluctant to take risks with new business opportunities because their frame of reference is not fit for the decisions to be taken. Different managers have different ideas about the business they operate in and these ideas can be visualized using this technique. In short, managers are asked what they think are the most important elements to be considered when making some decision. From the interview the researcher can derive statements that each link two elements in a causal relation. In the simplest case, one statement says ‘A leads to B’ another statement says ‘B leads to C’. When the statements are put together it results in a map with three elements and two causal relations. This same

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technique can be elaborated to produce collective causal maps that visualize the shared beliefs within a group of respondents (Scavarda et al. 2006). In this the researchers collect all the elements put forward by the respondents and choose a number of these to be analyzed further. The number of elements to be used is a matter of choice for the researchers. A greater number of elements might enhance the preciseness of the resulting map, but on the other hand this might compromise the overall picture.

Our analysis uses the same technique but instead of interviewing actors we derived the statements from texts. This was done here for each of seven reports that describe possible hydrogen futures (BMW Group 2006, Duwe 2003, EuropeanCommission 2003, EuropeanCommission 2006, HFP 2005, Vermeulen 2006, DOE 2002). For each report a separate causal map was drawn without pre-selecting a number of elements. These causal maps were then accumulated to form a single causal map that represents a consensus of ideas about the development of hydrogen. For clarity reasons we chose to use a limited number of elements. The remaining elements are the ones most prominent in the reports.

The resulting causal map can be seen a consensus of expectations throughout the reports. As the studied reports are in themselves also consensus reports of groups of participating actors, this map can be seen a strong representation of all stakeholders involved. Science, industry, governments, NGOs are all represented here.

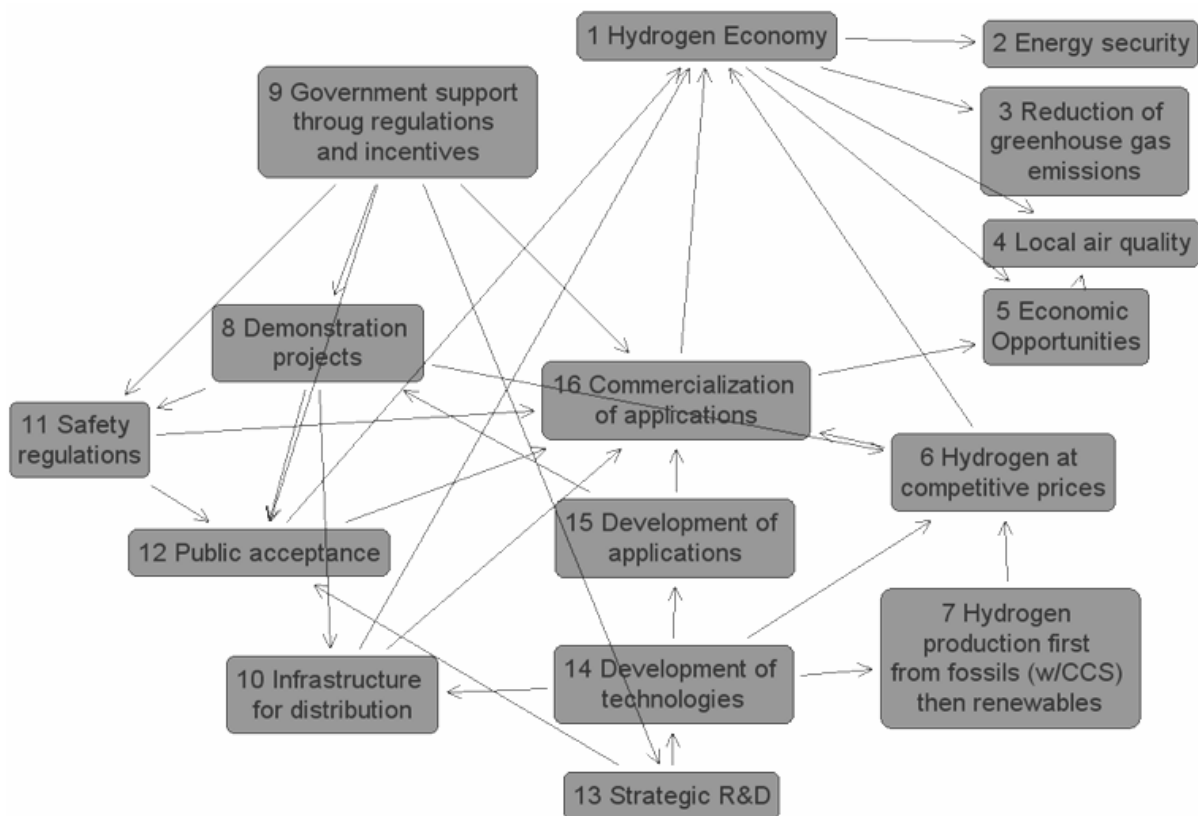


Figure 2: Collective Causal Map from vision reports

Observations from the Causal Map

First of all, the development of a hydrogen economy is represented as a chicken-and-egg dilemma, in which use (hydrogen cars) and availability (of hydrogen and the necessary distribution infrastructure) presuppose each other. The reports here all suggest some sort of solution to this dilemma. The solution is

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found in a gradual build up by instigating demonstration projects. These should not only result in proof of the technological feasibility but at the same time act as nuclei for growing networks of producers, infrastructure and users. If successful, a breakthrough of hydrogen is expected within 10 to 20 years, the exact moment however, is not shared by the reports. Before a breakthrough can take place, a number of elements require major efforts so that hydrogen energy systems can compete with competing alternatives. This is where the supposed causal relations become visible, element A requires work so that element B comes into existence and in turn will, after new efforts, result in C.

The biggest hurdle to be taken is the development of production methods for hydrogen. As hydrogen is only a carrier of energy, conversion methods have to be developed further. The current price of hydrogen production is considered to be too high for use in mobility. Development of technologies, economies of scale and increasing oil prices are thought to result in competitive costs. Growth has to be supported by governmental action, by means of funding research and, on the demand side, financial incentives for potential users of hydrogen vehicles and stricter emission regulations for conventional vehicles.

All reports expect a timeline in which hydrogen is produced by reforming natural gas and coal (with carbon capture and storage) first, and after some time renewable sources such as biomass, wind, and solar can enter the stage. Demonstration projects are expected to run on locally produced hydrogen because of a lack of infrastructure for transportation. A dissident opinion here is voiced by a number of NGOs that demand only climate-neutral production methods with the use of truly renewable energy sources.

No report challenges the assumption that hydrogen technologies will be developed to the necessary levels of efficiency, reliability and cost of production. This does require however that sufficient R&D funding is available and funding is strategically allocated and coordinated. Development is necessary for all aspects of the hydrogen chain: production, distribution, storage and use. The reports do not seem to doubt the timely development of these technologies and their ability to enable the transition pathway as described.

The results of technological developments and the build-up of infrastructure networks should be a number of usable and affordable applications for consumers and a number of viable business models on the business end.

The build up of a hydrogen infrastructure is thought to have two possible routes. The first is one starts with locally produced hydrogen until demand is large enough (breakthrough point) to legitimize nationwide distribution systems (network of pipelines). The second is a more gradual build up, starting in promising regions with a growing number of demonstration projects. Both pathways are expected to overcome the challenge of the before mentioned chicken-and-egg dilemma.

Public acceptance of hydrogen use appears as an important aspect in the reports. Acceptance should be elevated through demonstration projects and adequate safety regulations. Acceptance, defined as consumers' uptake of hydrogen technologies, can also be stimulated by regulations and incentives that support early adaptors.

Finally it is clear that widespread use of hydrogen cars should contribute to the solution of three major societal issues. 1. It should provide countries energy security by making them independent of diminishing oil reserves and reducing dependency on other countries. 2. It should contribute to a reduction of CO₂ emissions. 3. It should contribute to an improvement of local air quality. 4. It should provide an opportunity to develop new industries for hydrogen related products and services. This last issue seems mostly a point of concern within the European Union.

Prospective Chain of Functional Elements

For the remainder of this paper we focus on the column of four elements in the centre of the causal map. These represent the supposed linear causality of strategic R&D, technological development, development of applications and commercialization found in all reports. We will show that these elements are prospective structures that aim at mobilizing support for hydrogen technologies. What the reports are not clear about are the individual technological solutions for each of the shackles in the hydrogen chain. These shackles, or functional elements, featured in the reports are 1.production of hydrogen, 2.distribution, 3.storage and 4.utilization Because of the relatively (relative to commonly used fuels and accompanying technologies) underdeveloped status of these solutions, it is hard to select the winners beforehand. This uncertainty over the potential of individual solutions feeds competition between communities working on their development.

We present here a model of hydrogen technology selection in which a chain of functional elements has to be filled in by concrete technological solutions. This chain however is only prospective as it is only a projection of things that might come to being. In other words, technologies are continuously assessed for their fitness in relation to hydrogen energy systems even though no selecting actor knows exactly what specifications are required in the future. From the studied vision reports a number of potential solutions is derived that are continuously in competition to become the leading solution in the prospective hydrogen chain. It is important to note here that some solutions in fact pre-select one another. For instance fuel cells require highly purified hydrogen gas and some production methods are more suited to meet these requirements; electrolysis produces fare more pure hydrogen than steam reforming of coal.

In table 1 we present an overview of the most important possible solutions and apparent ‘common expectations’ connected to them. Because it is all to happen in the future, this competition is driven rather by expectations than by facts.

Table 1: Overview of possible solutions and ‘common expectations’

Element	Solution	Expected capabilities
Production	Natural Gas (CCS)	Practically all hydrogen used today is produced through steam-reforming of natural gas. This is expected to remain the common method for a couple of decades. With the addition of Carbon Capture and Storage techniques this should be near climate neutral.
	Coal (CSS)	For the long term coal could be used, after gasification, to produce hydrogen through steam-reforming as well. Cost and availability is better than for natural gas, but energy efficiencies are somewhat lower. Societal acceptance of using coal is questionable.
	Biomass	Biomass energy can be transformed using the principles of steam reforming. The energy efficiency of this pathway is questionable, so is the amount of biomass available for this purpose.
	Nuclear	Nuclear energy might be used to produce hydrogen through electrolysis, but this is a costly and not energy efficient route. Direct use of nuclear heat for thermal hydrogen production from water might prove to be an feasible route, but this will not be available for some decades.
	Electricity from renewable	Like nuclear electricity, costs are too high at this point to use the electricity to produce hydrogen. Hydrogen might be uses as storage medium in times of

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	sources	overcapacity. A lot is expected from further technological development 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 nanomaterials). Thermal splitting of water using 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. Build of this infrastructure would require sufficient demand for hydrogen and probably many years if not decades to construct.
	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 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 space.
	Liquid gas	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. Holds a promise for the future for being efficient in terms of energy and volume/kg hydrogen.

Utilization	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.
	Combustion engine	Proven technology that appeals to cultural annotations of the car. Less efficient than Fuel Cells, but cheaper to built.

Technological Communities

For a further analysis of the dynamics of expectations of these prospective solutions we will turn to the concept of technological communities. The concept as we use it was introduced by Rappa and Debackere (Rappa & Debackere 1992). It defines a technological community as a set of actors working on the same technology. For all of the solutions presented above there is a technological community working on the technology itself and its position in the prospective chain. These communities consist of actors throughout science and industry. Scientists work on basic development of knowledge and technological concepts, actors in industry work at the commercialization of products. All this work is done based on expectations of their technology. 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 their business.

For now we will not go into these differences in more detail and focus on scientists within the technological communities

Metal Hydrides Community

Scientists have to legitimize their research in order to receive funding from both government and industry. In most scientific fields this is done by showing its relevance for society and economy. Contributing to the prospective hydrogen economy is such a legitimization. For the community of our interest, metal hydrides for hydrogen storage, the hydrogen economy seems to fulfil this legitimizing function. Research in metal hydrides is done for many years, but since the late 1980's this community is associated with hydrogen energy systems. The basis principle this community studies and exploits is the absorption of hydrogen by metals. The H₂ molecule dissociates into two H atoms that each bind to the crystalline structure of the metal. Under thermal influence the hydrogen absorbs or desorbs which makes enables filling and emptying a storage tank (Dam et al. 2007).

Even though other storage systems, using compressed or liquefied gas, are proven technologies, metal hydrides have manoeuvred their way into the hydrogen visions. The community states that metal hydrides can potentially store and release hydrogen with higher energy efficiency. Furthermore metal hydrides can possibly store more hydrogen in the same tank size, which would increase the cars radius of action. These promised specifications have not been realized in practice but laboratory tests are 'promising'. Already, some niche markets make use of this technology but it should be said that these niche markets do not have the same requirements as the cars' market. For instance refuelling times and operating temperatures are major and fundamental hurdles for use in road vehicles, but for vessels (one niche market) this is less of an issue. The same goes for the weight and long-term refilling characteristics of metal hydrides; these are fundamental issues. Nonetheless metal hydrides are on the hydrogen agenda and are part of the strategic research agenda as shown in the causal map. To illustrate the struggle of this community to enter the agenda and remain on it we present figure 3. This shows that this community's work has become widely visible since the early nineteen nineties. In contrast, the fuel cell community was 'in' from the beginning, being the constituents of the vision (Goverde 2006). The graph suggests that attention for metal hydrides peaked around 2001, but it would require a more in-depth analysis to verify this.

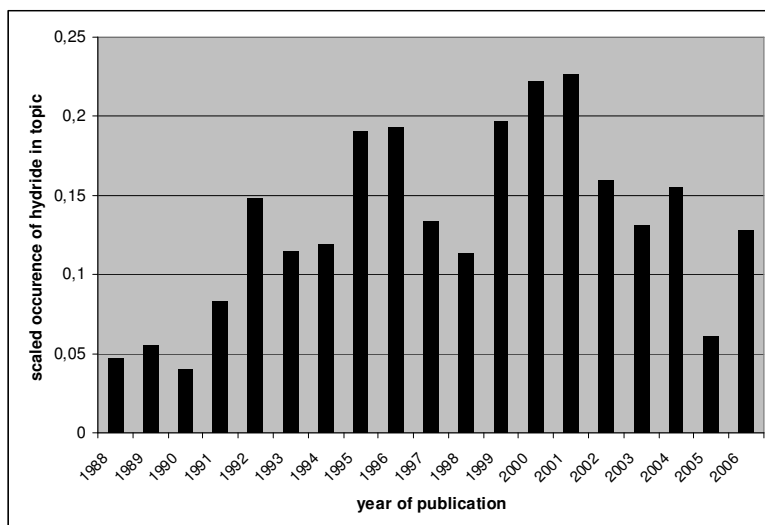


Figure 3: Occurrence of 'hydride' in article topics per year in the International Journal of Hydrogen Energy, scaled to the total number of articles per year in the journal

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Scientific publications from this community, dominated by Asian research institutes, all refer to the future of hydrogen technologies and the need for 'better' hydrogen storage solutions. By doing so, the communities contribute to expectations of metal hydrides and at the same time to expectations of hydrogen energy systems. If hydrogen energy systems disappear from the agenda of future energy systems, their work is rendered practically useless so they have every reason to contribute to these wider expectations. Because of this they are also dependant on other communities working on other functional elements such as utilization. For instance, if fuel cell costs are not lowered (or expected to become lower) in the future this might pose a threat to hydrogen technologies as a whole. Because of this interdependence all communities need to keep up expectations of their own technologies, of others, and hydrogen in general. As observed from a workshop on metal hydrides research in the Netherlands and tentative literature research we conclude that researchers in this field have expectations at four levels:

1. Expectations about their own research and design and its specifications in relation to others within their community
2. Expectations about other communities working with other approaches and heuristics on the same element in the hydrogen chain.
3. Expectations about the integration of different elements in the hydrogen chain.
4. Expectations about other, broader factors influencing the development and success of hydrogen as energy carrier

These expectations are, depending of the specific position of the actor within the technological community, communicated to convince technology selectors. Communities appoint spokespersons, who voice and defend expectations related to the higher levels of the hydrogen chain. These spokespersons not only defend the position of the community but also the hydrogen chain itself. Others in the community, PhD students as we observed, are more concerned with possible outcomes of their own research and their peers within the community.

Discussion

From an outsider perspective it might seem as if these interests are in line with each other, high expectations of metal hydrides ad to expectations of hydrogen energy systems and in turn high expectations of hydrogen ad to expectations of (the relevance) of metal hydrides research. We suspect that an in-depth study of these dynamics might reveal a somewhat more complex system. It might be so that the metal hydrides have joined the hydrogen bandwagon for the opportunities it grants them. On the other hand, from a hydrogen perspective it might be useful to have this community on board because it holds promises that other storage solutions can't offer. The point we make here is that the connection between hydrogen and metal hydrides is a construction that might very well be deconstructed once interests change. These concepts appear to depend on each other now, but in the future this might prove to be merely an opportunistic than a fundamental interdependence.

Another point that might come forward from an in-depth study is the coordination of technology development through expectations. Coordination here could mean the coordination of specifications that researchers aim for. These specifications are not a given and are in part dependant of developments of competitive solutions and of developments on the higher levels of hydrogen systems. Through these hypothetical dynamics it might be so that higher expectations of hydrogen systems lead to too high

requirements for a single solution such as metal hydrides. It could then turn out to be out selected because it can no longer match the requirements with its own expectations of future specifications.

A last point that we would like to study more in-depth is the vulnerability of expectations on the four levels we unravelled. By this we mean that expectations can be high of or low, but also very precise or more open to interpretation. Very high and precise expectations are useful when it comes to creating mandate, but at the same time they are vulnerable to disappointment if these expectations are not met. Expectations on the other hand that are less precise and therefore open to interpretations leave more room for error and are therefore not as vulnerable to disappointment. In our study we will try to quantify the preciseness of expectations within the community to be able to study these dynamics of expectations and disappointment.

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