Constructive Technology Assessment of the Hydrogen Transition in the U.S.

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Summary

Hydrogen is seen as a very promising fuel for the future and is expected to substitute the current petroleum regime. In this report a Constructive Technology Assessment (CTA) is conducted on the infrastructure related to the hydrogen economy. In a CTA the impacts of a technology on society and the assessment of these impacts by involved actors will be analyzed and suggestions for further development and decision oriented options are given in order to avoid negative consequences of the technological development. As a conceptual model for this CTA the system innovations approach and its multi-level perspective (MLP) has been used. Based on the three levels of MLP – micro level of niches, meso level of regimes and macro-level of landscapes – the hydrogen developments, the actions and positions of actors and its impacts have been analyzed. The research question I have focused on is '*How can we use the insights of a technology assessment of likely future hydrogen infrastructures for policy advice on current policies?*'

For the CTA an extensive array of literature and empirical data has been used. Apart from scientific literature and written empirical data, I have interviewed 15 actors with different backgrounds regarding the hydrogen transition. These actors were from involved industries, the government, research institutes and universities, and hydrogen associations.

In the U.S., and in most other developed countries, three important aspects that put pressure on the petroleum regime – the regime that plays a key role in the hydrogen transition and was the main focus of my research – can be seen today. These are environment, peak-oil, and geopolitics, with energy security as the main concern related to oil. These issues put pressure on the regime from both the landscape level, as from within the regime itself. These pressures create 'windows of opportunities' for new technologies.

Hydrogen is not an energy source, but an energy carrier and therefore it needs to be produced by using other energy sources. Influenced by the developments at the regime and landscape level many different hydrogen production technologies were, and are, explored and developed. The expectations are that natural gas will be the dominant technology in the near-term, in the mid-term coal and nuclear hydrogen technologies will join natural gas and only in the very long term renewable hydrogen technologies are expected to become the dominant technology.

Expectations and promises play an important role in the hydrogen transition. They create '*prospective structures*'; actions become coordinated through the prospect of a new technology and its functions while this emerging configuration is simultaneously shaping the technology to be. Prospective structures are actively created by actors involved in the hydrogen transition by means of articulation processes. These articulation processes therefore cause a significant pressure on the existing regime and are an important strategic move for new actors.

Many different actors play a role in the hydrogen transition and try to influence the process. The big energy industries, especially the oil industry, but also coal and nuclear industries, are the most powerful and position themselves in such a way that they create a favorable (future) situation for their industry. Apart from there influence on the

transition itself, they have a strong influence on the government. The oil companies have a strong incentive to control the transition process and even slow it down. Because of their size, capital strength and political influence they are more or less able to do that. Renewable industries are less influential, and got involved in the hydrogen transition mainly in order to protect their federal budgets. They do not particularly support a hydrogen transition. Other involved actors that have an influence on the hydrogen transition are environmental organizations, car manufacturers as users of hydrogen technologies, end-users, interest organizations, etc.

The most likely production methods that will emerge as dominant paths in the U.S. are natural gas for the short term, coal and nuclear for the mid-term. These paths are not only the preferred paths of the big industries; the U.S. government strongly favors these paths as well. Because of their 'scripts' these production paths require centralized production systems. There are several important impacts that follow from this centralized fossil and nuclear hydrogen path, of which the most relevant from a CTA point of view are 'environment and sustainability', the related to this 'non equal playing field', and the, to centralized production related, impacts, 'distribution network', 'oligopolistic regime structure', and 'freedom'

The assessments of the impacts by the actors vary considerably per actor (group). For most impacts there is a clear trade-off between economy on the one hand and the environment and society on the other. When it comes to environmental impacts, economic interests usually have the upper hand in actors' actions and decisions. This applies for industries, the government, as well as the public.

Hydrogen has the potential to change our present rigid centralized petroleum system in a decentralized fuel system. This has many technical, economical and social advantages. First, it can break down today's oligopolistic petroleum regime and can avoid the creation of new ones. Second, it has the potential to increase our personal freedom and autonomy. From a moral point of view decentralized systems are therefore more desirable than centralized. Reality is different though, since effective freedom and not having concerns about where the energy comes from are in general valued over autonomy.

The transition process is a very complex process and is difficult to steer. In order to avoid the negative impacts that come with the current transition path of fossil and nuclear hydrogen, current policies need to be changed. Measures can be taken at the different levels of the multi-level perspective. At the micro-level distributed renewable hydrogen production variations and niches need to be stimulated, especially hydrogen from wind and solar energy. The government should stimulate the developments of renewable variations by funding small innovative technology companies and larger technology companies that are not already major energy suppliers and universities. In addition to funding it is crucial that the selection environment in niches is influenced by, for example, subsidies, tax credits and technology-forcing regulations. Another way to put pressure on the existing petroleum regime is from the landscape level. The government plays an important role in changing the landscape level and with their regulations and policies they have a very powerful tool to increase pressure. The government, however, needs to be more influenced by other actors than just the big energy industries and pressure from below is required. Steering the developments thus requires a bottom-up approach. Small companies, universities, (left-wing) politicians and political parties, end-users, the public, etc. need to put pressure on the government and on the big industries in order to be able to steer the developments. Market-approaches seem favorable for the reduction of emissions, but in addition technology-forcing regulations are necessary to avoid that the 'market solution' goes toward centralized production systems again. It is important that a change in the public's perspective and behavior regarding environmental issues, and issues related to (de)centralized production, are stimulated as well. This landscape change, together with the democratization of the technological developments can influence both the government and industries.

The creation of technological nexuses, or the involvement of renewable industries in existing nexuses is important for the development of decentralized hydrogen production technologies as well. By not involving only them, but also increasing the active participation of the public and of environmental organizations in the discussion and development process, the hydrogen transition can be democratized and the pressure from the landscape level can be increased. Small companies, environmentalist, politicians, the public, etc. should more pro-actively pursue the creation of nexuses, but also the forming of alliances and partnerships.

The use of the MLP as a basis for a CTA is very useful. However, I encountered some problems with it. First, a normative assessment does not really play a role in the MLP, but it does in a CTA. Second, in the hydrogen transition many different regimes are intertwined, but the MLP does not really take into account the influences from other regimes. Third, although in MLP literature it is often stated that individual regime shifts will not affect the landscape dramatically, the transition from petroleum to hydrogen definitely has the potential to affect the landscape dramatically.

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Preface

It seems ages ago that I came to the University of Twente to start my bachelor program Civil Engineering. After one semester I indicated to my mentor that I wanted to start another major. Business Administration and Philosophy of Science, Technology and Society (PSTS) seemed to fit my desires best. Since Business Administration was closely related to my prospective management track in Civil Engineering I chose PSTS and started to take a course every now and then. Things went pretty well and after I got back from China where I finished my bachelor program Civil Engineering I had only 2.5 semesters left for my Master program PSTS. I decided to mainly focus on PSTS first, before finishing my Masters Civil Engineering. As one of the few students, I was committed to finding a challenge abroad for my Master's thesis. The PRIME Master Program was set up right in time for me to take part in it and in January 2006 I left for the U.S. to work on my thesis at Georgia Institute of Technology.

Although I consider myself more an engineer than a philosopher, something I realized once again the last six months, PSTS has been of great value to me. Many times people, especially Americans, have asked me questions like "what do you want to do with that?" or "is that good for your career?" Many times I answered 'I don't know, I just like it". Surprised faces were the result. Although I never had the intention to continue with a 'PSTS-career' and always saw engineering as my main focus, over the years I experienced the usefulness of PSTS for my personal development and academic skills, but also for my possible future career. Every engineer, manager, policy- and decision-maker benefits from a deeper understanding of science, technology and society.

I would like to take this occasion to thank all the people that contributed to my thesis and were of great help, both the interviewees at organization, as people at the University of Twente and Georgia Institute of Technology. There are a few persons I would like to mention explicitly. First of all Ellen van Oost. As my first advisor at the University of Twente, she played an important role in the accomplishment of my thesis. Moreover, it was because of her help that I had the opportunity to go to Georgia Tech for my thesis. From the University of Twente I also would like to thank Boelie Elzen, my second advisor for supervising my thesis and Adri Albert de la Bruheze as a third member of the graduation committee. From Georgia Tech I would like to thank Valerie Thomas for her help and input. She provided me with interesting material, helped me out in getting it, and kept me on track. I also would like to thank Philip Shapira, for making my PRIME exchange program possible. Finally I would like to thank my family and friends for their support and understanding.

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1. Introduction

Oil production is about to peak. When this will happen exactly is not clear and several studies make different predictions. However, most of those predictions are in the range of one or two decades. The steadily growing oil prices might indicate that the end is coming close. Moreover, the relation between greenhouse gases and climate change has become clear in many studies and is broadly recognized today. Finally, energy independence has become a popular and often discussed topic in politics. The need for alternative sources of energy to fuel our future economy is increasing and today hydrogen is 'the solution'.

In 2003 President Bush announced the Hydrogen Initiative in his State of the Union Address in February of 2003:

> *"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy" (Bush, 2003)*

In this address, President Bush called for $1.2 billion to be spent on hydrogen research to facilitate the transition to a "hydrogen economy". This was in response to a growing recognition that the U.S. dependence on oil comes with significant costs. Ever since, interest in hydrogen rose even more among industries, governments, and scientists.

As stated in the Address, hydrogen indeed has the potential for reducing the amount of greenhouse gases, like carbon dioxide, and air pollutants released into the atmosphere. Therefore it could play a role in reducing global warming and air quality problems in and around major cities. It can break the U.S. reliance on oil, and it can be a substitute for oil as a fuel in the future. However, hydrogen is not an energy source, but an energy carrier, like electricity. Therefore it needs to be produced by using other energy sources.

In my research I will take a closer look at the infrastructural aspects related to the hydrogen economy, particularly in relation to the transportation sector. Hydrogen can be produced from several different energy resources – fossil fuels, nuclear energy, or renewable energy – which is one of the advantages it can have for the future. This means that there is a broad range of possible future suppliers. What the future production method and energy source will be is unclear yet, but it is clear that different production pathways have different impacts on the above mentioned potential advantages of hydrogen and on society in general. The 21st century gives us the opportunity to make a shift from the polluting fossil fuel transportation era to a clean hydrogen future; now we only have to seize this opportunity and make sure that we aim at the right infrastructure.

1.1 Objective

In my research I have conducted a Technology Assessment (TA) on the infrastructure related to the hydrogen economy. Since the fuel cell vehicles (FCVs) will be available on the market in a relatively near future, it is important to analyze the possible future supply side related to it. At this moment steering and control of the infrastructural system is still possible before any negative consequences will happen or undesired directions are taken. This is necessary before huge investments are made in the development and construction of an energy infrastructure – which will last for over 50 years – that turns out to be not the best solution for the future. In a TA the impacts of a technology on society and the assessment of these impacts by involved actors will be analyzed. Based on this, suggestions for further development and decision oriented options can be given in order to avoid negative consequences of the technology. Insights from a TA can provide valuable inputs to decision and policy makers, managers, R&D departments, etc.

1.2 Research Question

The research question I will focus on in this TA is:

How can we use the insights of a technology assessment of likely future hydrogen infrastructures for policy advice on current policies?

This question can be split up in several sub questions:

a) *What are likely infrastructures for the future hydrogen economy?*
b) *How does the existing regime influence and control the developments and policies, and what social mechanisms play an important role in the developments?*
c) *How are the impacts of these infrastructures assessed?*
d) *How can the developments be controlled or steered?*

1.3 Overview Report

For a better understanding of these research questions and to root my research in literature, I will first discuss the underlying theoretical concepts that will be used for my analysis. After that, in chapter 3 I will describe the methodology that I have used for my research. In chapter 4 an exploration of the hydrogen technology is given. The future expectations about the hydrogen transition are discussed here. Chapter 5 gives an extensive description and analysis of the involved actors, their interests, position and actions in the hydrogen transition. This is followed by Chapter 6, in which after an analysis of the impacts of the hydrogen transition, a normative assessment of these impacts is given. This will lead to Chapter 7, the feedback. The last chapter is the conclusion.

2. Theory

In this Chapter I will discuss theoretical concepts that are of importance to my research and form the basis for it. First, I will further elaborate the concept ‘Technology Assessment’. Secondly, I will discuss the widely used concepts of ‘Social Shaping of Technology’ (SST). This will lead to the discussion of ‘System Innovations’ and the ‘Multi-Level Perspective’ (MLP), which will serve as a conceptual model for my research. In technological change and MLP expectations and promises play an important role, which will be discussed at the end of this chapter.

2.1 Technology Assessment

Technology Assessment attempts to provide policymakers with a rational basis for their decisions. The classic aim of technology assessment is ‘to identify technology induced risks early enough, to analyze in detail the range of possible social, economic, legal, political, cultural and ecological effects, to process investigation results in a problem oriented manner, to present alternative decision oriented options, and at the same time to point out the various social interests and value judgments linked with the development and use of new technologies’.[1] The process of technology development is heterogeneous. For this research I will make use of a Constructive Technology Assessment (CTA). Constructive Technology Assessment is a type of TA rooted in the social constructivist ideas in Science and Technology Studies (STS). The conceptualization of technological development as a fundamental social process opens possibilities for integration of assessment insights into the development of the technology itself (this is where the notion “constructive” is referring to).[2] In this social construction of technology, not only policy makers are addressed as target group but also engineers and designers. Interaction with scientists, engineers and designers, policy makers/actor groups from the envisaged user situation and CTA analysts is central (that is: variation environment, selection environment and CTA analysts).[3]

CTA pays attention to the steering of the internal development of the technology. It is based on the idea that during the course of technological development, choices are constantly been made about the form, the function, and the use of that technology and, consequently, that technological development can be steered to a certain extent (Schot, 1992). For the use of CTA, Schot proposes a co-evolutionary model, in which variation and selection are neither independent nor coincidental processes. Since heuristics is present, technological developments follow quite specific directions, while other possible directions are ignored (this is also known as ‘path dependency’). The content of technological development is shaped simultaneously with the context. Variation and selection are linked by actors, resulting in the actor role labeled ‘technological nexus’. The nexus role implies considering both the selection and variation process as a resource and an option: that is, activities that can and must be molded and harmonized through

[1] Institute of Technology Assessment, Austria: http://www.oeaw.ac.at/ita/ebene3/e2-1a.htm
[2] Handout for the course ‘Designing the Future: Technology Assessment and Forecasting’, October 2005
[3] Ibid

active efforts. In most cases the nexus is specific, describing the relation between technological variation and environmental selection.

Another way actors link variation with selection is by niche management. This co-evolutionary model suggests three general CTA strategies to alter current lines of technological development: the development of alternative variations; modification of the selection environment; the creation or utilization of technological nexus. Governments clearly rely heavily on strategies of stimulating alternative variations through funding and subsidies and changing selection through regulation (Schot, 1992). I will discuss 'niches' in more detail in section 2.5.3.

Fuel cell vehicles (FCVs) are an existing technology which is not in the early phase of development anymore. Many efforts in the development, however, are still necessary in order to put valuable products on the market. Moreover, as indicated before, successful implementation relies heavily on the development of the whole system; not just the fuel cells, but also, among others, the required infrastructure. Since implementation of fuel cells on the market seems to come close (today they are used, but only in demonstration projects), it is important to conduct a CTA on the infrastructural services and installations, to analyze the possible future consequences and risks of the technology, on social, economic, legal, political, cultural and environmental level. By looking at social interests, value judgments and alternative design and decision options a rational basis for decision-making is provided to policymakers, managers, developers, etc. in order to steer the developments of the technology in the 'right' direction, away from undesirable impacts.

CTA has its roots in, the in literature widely discussed, Social Shaping of Technology (SST). In the next section I will discuss this popular theory.

2.2 Social Shaping of Technology

The term social construction started to become common in science and technology studies in the late 1970s. Since then, important texts have claimed to show the social construction of facts, knowledge, theories, phenomena, science, technologies, and societies. For science and technology studies, social constructivism provides three important reminders. First is the reminder that science and technology are importantly social. Second is the reminder that they are active. And third is the reminder that science and technology do not provide a direct route from nature to ideas about nature, that the products of science and technology are not themselves natural (Sismondo, 2004).

In their first edition of 'the Social Shaping of Technology' MacKenzie and Wajcman introduced the metaphor of 'social shaping of technology' (SST), rather than the more popular 'social construction', in part because, according to them, the latter is too prone to the misconception that there was nothing real and obdurate about what was constructed. What is being shaped in the social shaping of artifacts is no mere thought stuff, but obdurate physical reality (MacKenzie and Wajcman, 1999). I will use both terms alternately, considering them as alike.

In the view of SST the 'black box' of technology must be opened, to allow the socio-economic patterns embedded in both the *content* of technology and the *process of* *innovation* to be exposed and analyzed. SST emerged through a critique of ‘technological determinism’, which is, in general, the theory that technology is an independent actor, and that changes in technology determines social changes. As a contradictory, in SST technology is a social product, patterned by the conditions of its creation and use. Central to SST is the concept that there are ‘choices’ (though not necessarily conscious choices) inherent in both the design of individual artifacts and systems, and in the direction or trajectory of innovation programs (Williams and Edge, 1996). These choices, as well as technological developments, are seen as a social phenomenon. Usage and meanings, given to a certain technology by users, play an important role in this process. Technology does not have its own life but is shaped by society; there is an interaction between context and content, a co-evolution (see section 2.3). In a broad sense the sociology of technology is concerned with explaining how social processes, actions and structures relate to technology. Within social constructivism the focus is on the social, political and economic forces which give rise to particular technologies (Mackay and Gillepsie, 1992).

One of the most well known approaches of social construction is the Social Construction of Technology (SCOT) of Pinch and Bijker. In SCOT the developmental process of a technological artifact is described as an alternation of variation and selection: variation refers to the development of the technology itself, the content; selection refers to the development of the environment of the technology, the context. This results in a multidirectional model, in contrast with the linear models used explicitly in many innovation studies and implicitly in much history of technology (Pinch and Bijker, 1984). Linear models conceived of innovation as involving a one-way flow of information, ideas and solutions from basic science, through research and development, to production and the diffusion of stable artifacts through the market to consumers (Williams and Edge, 1996).

SCOT emphasizes the artifact, its ‘relevant social groups’ and the ‘interpretative flexibility’ of an artifact: different social groups associate different meanings with artifacts leading to interpretative flexibility appearing over the artifact (Kline and Pinch, 1999). Moreover, it points to closure, the ways in which innovation may become stabilized. Bijker and Pinch's focus is not just on the symbolic meaning of technologies but includes also variation in criteria for judging whether a technology 'works' (MacKenzie and Wajcman, 1999).

Although SCOT has been refined and developed over the last decade, important weaknesses have appeared. First, SCOT as originally conceived dealt mainly with explaining the social process of the conception, invention, design and development of technology. It fails, however, to take account of ideology in the social shaping of technology, to consider marketing as a process which is central to the shaping of technology and, finally, it fails to take account of the appropriation of technologies by users (Mackay and Gillepsie, 1992).

The second important weakness is that SCOT, as many commentators have remarked, said little about the social structure and power relations within which technological development takes place (Kline and Pinch, 1999). Especially this point is of great relevance in the discussion about the future hydrogen infrastructure. Regarding hydrogen, and the energy industry more general, there is much more at stake than just technological developments. Politics and power relations seem to play an important role in the discussion. The oil industry, for example, is one of the big sponsors of political campaigns and has been able to influence many policies in history.

This second weakness is often remarked by proponents of the neo-Marxist approach who argue that, instead of focusing at the micro level, we need to examine how wider, macro socio-economic forces affect the nature of technological problems and solutions (Mackay and Gillepsie, 1992). This approach criticizes the social constructivist approach, but also the actor network approaches – which are a reaction to a concern related to this second weakness: the neglect of the reciprocal relationship between artifacts and social groups (Kline and Pinch, 1999; MacKenzie and Wajcman, 1999) – and the systems approaches for ignoring the political and economic context within which a technology is developed (Mackay and Gillepsie, 1992). Too much power and autonomy is ceded to individual actors, rather than to existing structures of power and interests (Williams and Edge, 1996). Russell (1986) puts it this way:

> "Far beyond just 'identification' and 'description', groups need *locating* in a structured and historical context. That is, we need to map out not only their relation to the technology, but their relations to other sections of society, the economic, political and ideological constraints and influences on them, the broad historical changes affecting them and the more specific events leading them to the process under investigation. It is this structural location that largely determines the relationship to each technology which they conceive or which confronts them..." (pp. 335)

In Russell's opinion it is, instead of looking at the limited micro focus of the SCOT approach, better to situate social processes producing technologies in an established framework and in a wider context of social analysis. Then it is possible to relate the micro level to a broader social structure and process. He states that in political processes in particular, the analysis of technology and technological change desperately needs a better framework to avoid the empiricism and implicit pluralism which has characterized many case studies. Therefore Russell argues that regarding the analysis of political processes behind technology we must consider what is peculiar about the material and ideological properties of existing technical systems – themselves the cumulative product of previous such processes – into which alternative innovations would have to fit: for example, the roads, fuel supply, the manufacturing industry itself, etc. Such systems provide different barriers to the introduction of each option. we may not be able to resolve whether such constraints are real, contrived or imagined, but we must at least show whether and how arguments about them were deployed by each group in debate and decision-making (Russell, 1986). This consideration of the wider context of social analysis is very important in relation to FCV and the hydrogen economy. As mentioned before the system is wider than just the fuel cells; hydrogen production, distribution, fuelling stations, storage, they all provide different barriers. And regarding the hydrogen production, it is not just the fossil fuels industry that is involved, but also the nuclear, renewables, etc.

Regarding technological change, a central aspect in this research, one of the approaches in literature that indeed consists of a broad framework and looks at existing technical systems is the, in the Netherlands developed, System Innovations approach. As we will see this approach takes into account both micro, meso and macro level, and both social and economic structures. This approach is considered to be important to solve problems regarding societal functions fundamentally, as is argued in the fourth Dutch National Environmental Policy Plan (Elzen et al, 2004). Transportation and energy supply systems are amongst these societal functions and this approach therefore seems to be suitable for my research regarding fuel cell vehicles and hydrogen. Before I will discuss this approach in more detail, I will first briefly explain the already mentioned concept of 'co-evolution', since the overall pattern of technical changes is one of co-evolution (Rip and Kemp, 1998) and the System Innovations approach – as well as CTA – heavily relies on this concept.

2.3 Co-evolution

Co-evolution is increasingly recognized as an important issue, e.g. in evolutionary economics, long-wave theory, innovation studies. It has always been an important theme in science and technology studies, with its emphasis on seamless webs, emerging linkages between heterogeneous elements and co-construction (Rip, 2002).

Co-evolution is often used as a broad characterization of co-development and mutual shaping, without specific reference to evolutionary theory. It deals with "bridging of the gap" between science and technology on the one hand, and society on the other hand. Nowothny et al emphasize the co-evolution of science and society, not as a theory, but as a diagnosis, and a plea for more interaction between science and society (Rip, 2002). They state that co-evolution "denotes an open, and certainly more integrated, system of science-society interaction which enhances the generation of variety, whether in the choice of scientific problems, colleagues or institutional designs, on the one hand, or the selective retention of certain choices, modes or solutions on the other hand" (Rip, 2002). Under such a broad heading, interactions between (science,) technology and society can be studied.

The link with explicit evolutionary and co-evolutionary theory is sometimes made, but often it is only the overall connotation of the terms 'evolution' and 'co-evolution' that is used. A key point is that patterns occur in co-evolution, and that some of them stabilize and shape further actions and interactions; a well-known example is a technological regime (to which I will come back later). Actors experience the constraints of such a regime. In open and fluid situations, they might actively try to create a regime that is of advantage to them (for example in the battle about an industry standard) (Rip, 2002).

The process of co-evolution can, and will, be modulated by actors (the rough agreements and networks, for example), and this also allows a productive role for governments. But processes of co-evolution cannot be shifted at will in any desired direction. A certain nonmalleability characterizes technology, not because actors have insufficient power or resources to get what they want, but because technological developments have, in a sense, the rules of their own: from the heuristics in search processes to the normal ways of doing things in a technological regime. These rules are outcomes of action and interaction, leading to the particular form that irreversibilities take in the situation of technical change in societies. Because such rules function at a collective level, they cannot be changed easily by any one actor (Rip and Kemp, 1998).

Co-evolution is the linked evolution of two (or more) dynamics, each of which can be conceptualized in terms of variations and selections (and retentions). The linkage may give rise to patterns with dynamics of their own. For actors, there is the experience of co-evolution (in terms of mutual interdependencies, and the force of path dependency) and anticipation on selection, as well as, even more precariously, anticipation on emerging patterns (Rip, 2002).

Improving outcomes is possible for each actor through a better understanding of their selection environments and the dynamics of co-evolution. Since other actors will react, the improved strategies cannot be stable. In fact, an enlightened actor understands his action as modulation of interactions and emerging patterns of which he himself is a part, rather than linear steps toward goal achievement. The same holds for actors with a governance responsibility (governmental or otherwise). Modulation of ongoing processes rather than forceful shaping is the enlightened approach (Rip, 2002).

It is these dynamics of co-evolution that play an important role in system innovations, as we will see in the next section.

2.4 System Innovations

In recent years, there is increasing interest in transitions and system innovation at the level of societal functions such as transportation, communication, housing, energy supply, feeding. Societal functions are fulfilled by sociotechnical systems, which consist of a cluster of elements, including technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks. A transition is a shift from one sociotechnical system to another, i.e., a system innovation. System innovations are co-evolutionary processes, which involve technological changes, as well as changes in other elements, such as user practices, regulation, industrial networks, infrastructure, and symbolic meaning (Geels, 2002a; Geels, 2005a; Geels, 2005b). This emphasis on the co-evolution of technical and societal change distinguishes transitions from more incremental processes of innovation which are primary characterized by technical development (successive generations of technologies) with the societal embedding of these technologies changing relatively little (Elzen et al, 2004). A transition from our present petroleum based system towards a future hydrogen based system requires us indeed to look at the co-evolution of technical and societal change, since not only the involved technologies will (have to) change, but also policies and regulations, the consumption of energy, power relations in politics, business, etc. and power relations between the Middle East and Western Countries. According to Rifkin (2002) hydrogen, that has the potential to bring about a decentralized energy system, will give rise to a wholly new type of energy infrastructure as well as to radically different economic institutions and new patterns of human settlement, just as coal and the steam engine and, later, oil and the internal combustion engine did in the past. When every human being on earth can be the producer of his or her own energy, the very nature of commercial life radically changes. Economic activity becomes far more widely diffused and this would make possible the establishment of human settlements that are more widely dispersed and more sustainable in relationship to local and regional environmental resources.

Transitions and system innovation are thought to be promising to achieve jumps in environmental efficiency. In transport systems, energy systems, agricultural systems etc., there are promising new technologies with better environmental performance. But many of these new technologies are not (yet) taken up. This is partly related to economic reasons, but also to social, cultural, infrastructural and regulative reasons (Geels, 2002a; Geels, 2005b). The 'chicken-egg' problem related to fuel cells and the hydrogen economy illustrates this problem: manufacturers of FCVs are not willing to invest a lot of money in the development when a decent hydrogen infrastructure is absent. Investing in an infrastructure on the other hand is not attractive when there are only a few vehicles running on hydrogen yet (Romm, 2004). The different elements in a system are linked and aligned to each other and therefore the existing systems are 'locked in' at multiple dimensions and are stable and not easy to change. Radically new technologies have a hard time to break through the existing systems. Hence, the analytical focus in academic sustainability analyses has widened from artifacts to sociotechnical systems (Geels, 2002a; Geels, 2005b).

Innovation systems can be defined on various levels, e.g., national, regional or sectoral systems of innovation. An important insight from the systems of innovation approach(es) is the emphasis on interlinkages between elements and co-evolutionary processes. But the main focus in the systems of innovation approach is on the functioning of systems rather than the change of systems. Hence, a recent review of the sectoral system of innovation approach noted that one of the key questions that need to be explored is: how do new sectoral systems emerge, and what is the link with the previous sectoral system? (Geels, 2005b)

System innovations involve simultaneous processes on multiple dimensions and levels. They are a blend of longer term and shorter term processes. System innovations require that these processes link up and reinforce each other. The so-called multilevel perspective (MLP) has been developed to analyze and explain transitions and system innovations (Elzen et al, 2004). I will describe this perspective in the next section.

2.5 Multi-Level Perspective (MLP)

The multilevel perspective was originally developed to understand regime shifts. To that end, three levels were distinguished: the micro level of technological niches, the meso level of technological regimes and the macro level of socio-technical landscapes. The conceptualization of dynamics at these levels aims to combine insights from evolutionary economics, innovation studies and science and technology studies (Geels, 2005b).

2.5.1 Technological Regimes

The meso level of technological regimes is crucial in the multi-level framework. The concept of 'technological regimes' stems from evolutionary economics, where it was coined by Nelson and Winter to explain the occurrence of technical trajectories. Nelson and Winter state that technological regimes refer to cognitive routines that are shared by engineers and designers in different companies (Kemp et al, 1998; Geels 2002a; Geels, 2005b). According to Rip and Kemp (1998), however, emphasizing the artifact and technologist runs the risk of underconceptualizing the social environment into which the novelty is introduced. Technologists tend to see their environments only in terms of opportunities and constraints for the introduction of the new project. But, in fact, the social environment has its own dynamics, and it has already shaped the opportunities for, as well as the ideas about, the novel configuration. Therefore, structural aspects of the environment of technologies, and existing systems and socio-technical landscapes, must be taken into account. Rip and Kemp (1998) therefore introduce a wider definition of technological regime. They define it as:

‘the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems - all of them embedded in institutions and infrastructures’ (p. 338).

These rules, which are cognitive, normative and formal, are much wider than the cognitive routines Nelson and Winter refer to. Moreover, according to Rip and Kemp's definition rules are embedded not only in the minds of engineers, but also more widely in the knowledge base, engineering practices, corporate governance structures, manufacturing processes and product characteristics (Geels, 2005b). Examples of such rules are: the search heuristics of the engineers, technical standards, the rules of the market in which firms operate, the user requirements to be accommodated at any given time, and the rules laid down by governments, investors and insurance companies. These rules guide (but do not fix) the kind of research activities that companies are likely to undertake, the solutions that will be chosen and the strategies of actors (Geels, 2002b).

This widening of the definition means that more social groups are taken on board than engineering communities. Technical trajectories are not only influenced by engineers, but also by users, policymakers, societal groups, suppliers, scientists, capital banks etc. These wider embeddings make rules, which have both enabling and constraining effects, harder to change (Geels, 2002a and 2005b). Because the activities of these groups are also guided by rules, Geels (2002a) proposes to further widen the scope from technological to socio-technical regimes to refer to the semi coherent set of rules carried by different social groups and to understand coordination between the different groups.

2.5.2 The Socio-technical Landscape

Technological trajectories are situated in a ‘socio-technical landscape’, consisting of a set of deep structural trends external to the regime. The analytical importance of ‘landscapes’ is that they form an external structure or context for interactions of actors. While regimes refer to rules that enable and constrain activities within communities, the ‘socio-technical landscape’ refers to a wider technology-external context or external environment, which cannot be changed at will by regime actors. The context of landscape is even harder to influence than that of regimes. It mostly results from the juxtaposition of the dynamic in a variety of regimes. With regard to technological trajectories, the landscape can be understood as providing a ‘gradient’ or backdrop for development. This means that the landscape makes it easier for technical trajectories to go in certain directions rather than others (Geels, 2002a; Elzen et al, 2004; Geels, 2005b).

The content of the socio-technical landscape is rather heterogeneous and may include aspects such as economic growth, emigration, brought political coalitions, cultural and normative values, environmental problems, resource scarcities, oil prices and wars. The metaphor ‘landscape’ is chosen because of the literal connotation of relative 'hardness' and the material context of society, e.g. the material and spatial arrangements of cities, factories, highways, and electricity infrastructures (Rip and Kemp, 1998; Geels, 2002a; Geels, 2005b).

2.5.3 Niches

While regimes usually generate incremental innovations, radical innovations are generated in niches (Geels, 2002a). Most inventions are initially relatively crude, have low technical performance, and are cumbersome and expensive. Because such innovations cannot survive and compete in normal, mainstream markets, they need some protection. This protection is provided by niches, in which the selection criteria are very different from the regime. Niches are actively constructed by incubators or product champions. These actors are able to rouse the interests of other actors (for example, policymakers, users, suppliers) to mobilize resources for further development work of the innovation, by making promises about possible functionalities and market applications (Van Lente and Rip, 1998; Geels, 2002a; Geels, 2005b). Their activities lead to a support network of actors, who are willing to put time and money into nurturing and developing the innovation. These networks of actors expect or have a strategic vision that the innovation can be developed as a viable market product (Elzen et al, 2004; Geels 2005b). Because niches offer some protection, they act as 'incubation rooms' for radical innovations (Geels, 2002a; Geels, 2005b). In these first niches commercial viability might well be absent. The first applications of electricity at world fairs, theaters and public events had symbolic value; they brought excitement. The first applications of airplanes and cars in races were never commercial successes; indeed, the motivation to engage in such activities was not primarily economic in nature (Hoogma et al, 2005).

Niche developments happen in two (partly overlapping) forms: technological niches, and market niches. Niche development starts in protected spaces, were regular market conditions do not prevail because of special conditions created through subsidies and an alignment between various actors. These technological niches are often played out in the form of experiments like those with electric vehicles in various European countries in cities. Technological niches can develop into market niches - application in specific markets in which regular market transactions prevail (Geels, 2002b; Geels, 2005b)

These niches are important for the development of a new technology, underpinning the take-off of a new regime and the further development of a new technology. They provide space for such key processes as: network formation, coupling of promises and expectations, and learning and articulation processes on issues like technology, user preferences and practices, regulations, and so on (Geels, 2002b; Elzen et al, 2004).

2.5.4 The Sociological Characteristics of the Three Levels

The relation between the three concepts can be understood as a nested hierarchy or multi-level perspective. The nested character of these levels, means that regimes are embedded within landscapes and niches within regimes. In figure 1 this embeddedness is indicated with dotted lines. Multiple regimes are embedded in the same landscape, and multiple niches in a particular regime (Geels, 2002a; Geels, 2005b).

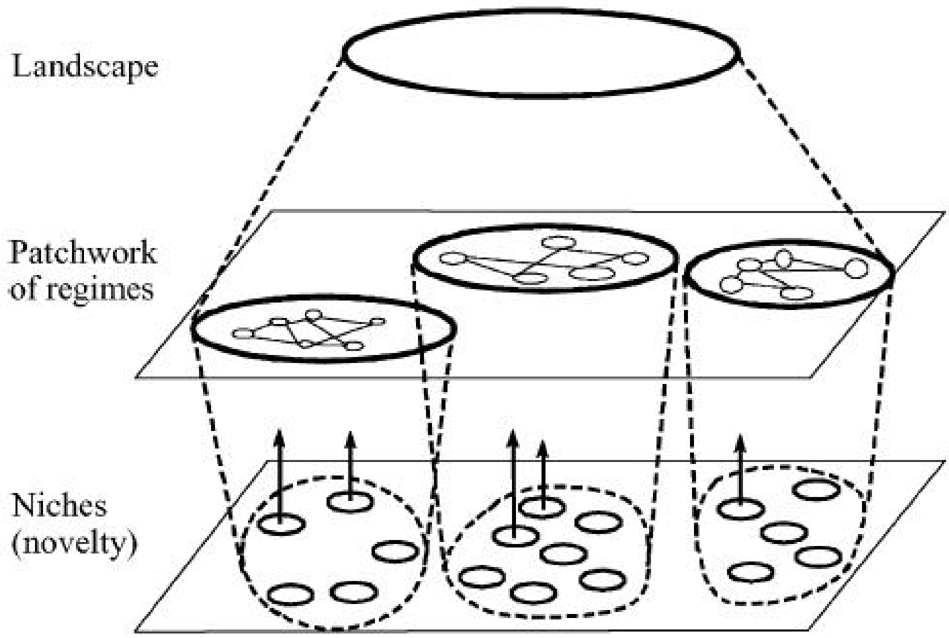

Figure 1: Multiple levels as a nested hierarchy (Geels, 2002a)

The multilevel framework is based on sociological concepts, with a focus on activities of people and the rules, which provide the context for action and interpretation. On the one hand people act on the basis of rules, but on the other people learn from their actions and may change the rules. The (socio)logic of the three levels is that they provide different kinds of structuration of activities in local practices (Geels, 2005b):

The rules in technological niches are vague and imprecise; for example, diffuse promises about potential uses and different ideas about best search directions. There are no specific rules that guide activities. The activities of actors in a niche go in many directions and there is experimentation and uncertainty. The niche rules provide only loose structuration; the rules have no strong coordination 'power' on actors.

In technological regimes, structuration of activities in local practices is much stronger than in technological niches. A reversal has occurred. While actors put in a lot of effort to articulate and uphold rules in niches, the rules have become 'stronger' in technological regimes. They have strong coordinating effects on the activities of actors in local practices. The rules do not determine action, but strongly guide them. It is possible to deviate, but this is difficult, and takes a lot of effort. Social conventions and rules in (technical) communities are not easy to change.

Socio-technical landscapes provide even stronger structuration of local activities. Material environments and widely shared cultural beliefs, symbols and values are hard to deviate from. They form gradients for action. Landscapes are more difficult to change than regimes.

2.5.5 Dynamics of System Innovation

The multilevel perspective has been used to understand the emergence and diffusion of new technologies. An important point of the MLP is the dynamic interaction between the multiple levels (Geels, 2005b).

Novelties emerge in niches in the context of existing regimes and landscapes with its specific problems, rules and capabilities. Novelties are produced on the basis of knowledge and capabilities and geared to the problems of existing regimes. Niches are crucial for transitions and system innovations, because they provide the seeds for change (Geels, 2002a; Geels, 2005b). Figure 2 shows how transitions start in niches. The downward arrow from the regime level is solid, while the arrow from the landscape is dotted. This is meant to indicate that the influence from the regimes on niches is stronger and more direct than the influence from landscapes, which is more diffuse and indirect (Geels, 2002a; Geels, 2005b).

After successful application in one domain, the technology finds through a series of new applications that become attainable because of its progressive improvement in terms of performance characteristics and economics. This is the process of niche branching, which includes the emergence of new application domains and the creation of the bandwagon effect (that is, a wider diffusion) through replication of the niche elsewhere. The changes brought forth by this process of niche branching culminate in the emergence of a new technological regime by coupling to developments on other levels (Hoogma, et al, 2005). This process is indicated with a '2' in figure 2.

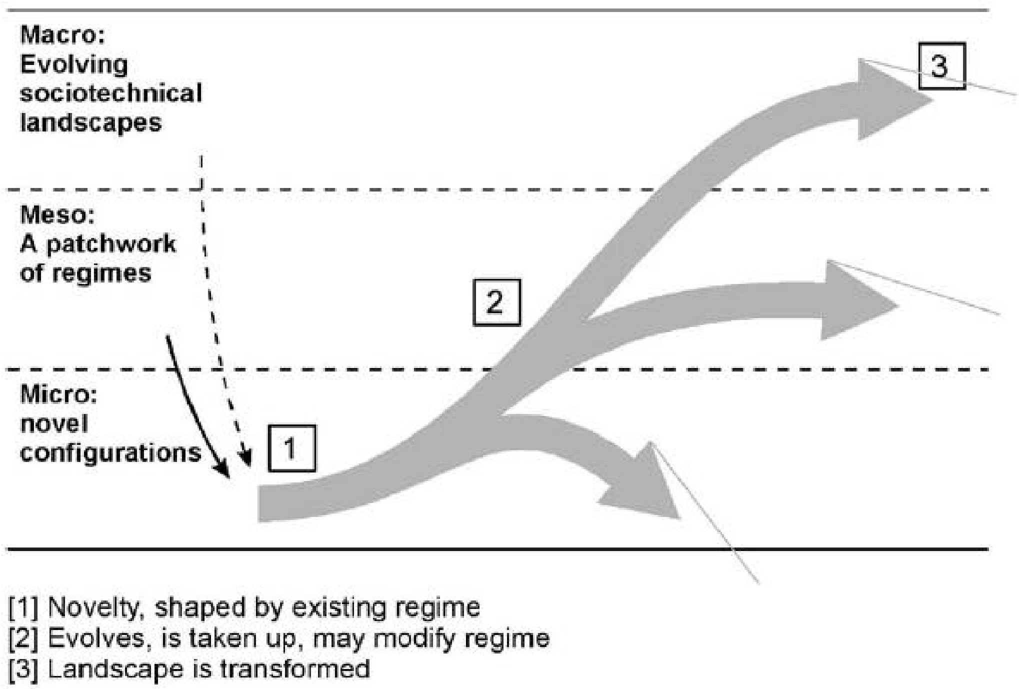

Figure 2: The dynamics of sociotechnical change (Geels, 2002a)

The important point of the multi-level perspective is that the further success of a new technology is not only governed by processes within the niche, but also by developments at the level of the existing regime and the sociotechnical landscape. Changes at the landscape level, for instance, may influence the development of technologies embedded in regimes as well as new promising alternatives by putting pressure on the regime, and creating openings for new technologies (Geels, 2002a; Geels, 2005b; Hoogma et al, 2005). Or as Elzen et al (2004) state it: "Radical innovations form the seeds for transitions and their chance of breaking through can increase when the existing regime becomes less stable, through internal problems or negative externalities that cannot be solved adequately" (p. 254). The development of the FCVs and a hydrogen economy, for example, is strongly influenced by the increasing need for cleaner fuels to solve the environmental problems that came with our existing fossil fuels regime. Moreover, the 'end of cheap oil', an aspect that causes significant internal pressure in the petroleum regime, has a strong influence on the development of alternative fuels and energy sources. On the other hand, the landscape is, however, not directly influenced by the success of local innovation processes and only to a limited extent by individual regime shifts. Of course, if a number of regime shifts occur, the landscape will be changed (Hoogma et al, 2005).

The concept of technological regimes helps understand inertia in socio-technical change (e.g. car manufacturers stick to gasoline engines), due largely to the embeddedness of existing technologies in broader technical systems, production and consumption patterns, belief systems and values, which creates economic, technological, cognitive and social barriers for new technologies (Geels, 2002b; Hoogma et al, 2005).

Because of the inertia of incumbent technologies, many new technologies remain on the shelf. For instance, the new product may require different knowledge and capabilities, new production techniques and skills that may not be available. Their use and development may require complementary inventions and changes in organization (in production routines, in plant and factory layout) plus changes in the institutional context (in regulation, fiscal policies and social norms and values). These are known to come about slowly (Geels, 2002b). In a transition to a hydrogen economy these changes will play an important role and are important to look at.

Next to the crucial processes in niches and the developments at the level of the existing regime and the sociotechnical landscape, a third important aspect is the role of actor strategies and social mechanisms. The convergence of processes at multiple levels increases the chance of regime transformation, that is, it creates the 'right' circumstances. Although processes at different levels can converge and create opportunities, the actual linkages always need to be made by actors in their cognitions and activities. Social mechanisms can speed up or accelerate this process (Geels, 2005b). At the same time, however, social mechanisms can slow down the process, because of the strategic opposition from firms vested in the old technology, as such technologies may erode the value of past investments and cause anxiety in the organization (Geels, 2002b). These actors have vested interests in the existing system and invest in incremental innovations to improve its performance (Elzen et al, 2004). The car and oil industry seem to be an example of these actors related to FCVs and alternative fuels. By thwarting policies and by improving the existing system (development of more efficient internal combustion engines and more efficient oil production methods) they try to slow down the transition process.

Geels (2002a and 2005b) made several additions to the MLP and refined figure 2. To counter the bias towards the novelty, Geels argues that more explicit attention needs to be paid to ongoing processes at the *socio*-technical regime and landscape levels, for example, emergence of new markets, policy dynamics and new technologies which can act as stepping stones. According to Geels, regimes should be analyzed not only as barriers, but also as opportunities. As a heuristic, Geels (2002a) has distinguished seven dimensions in the sociotechnical regime (figure 3): technology, user practices and application domains (markets), symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge. The regular ongoing incremental processes are represented with relatively long arrows. Although the different dimensions are linked and co-evolve, they also have internal dynamics. This may result in 'tensions', represented in figure 3 with shorter diverging arrows, indicating uncertainty and differences of opinion. Tensions may lead to periods in which linkages are weakening or 'loosening up'.

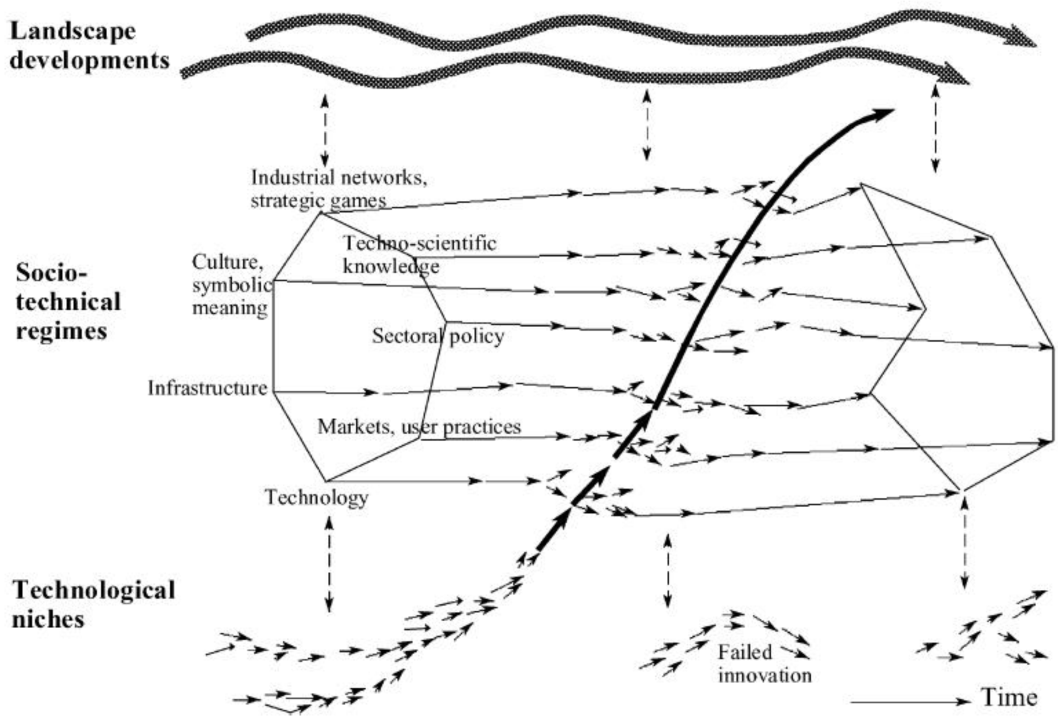

Figure 3: A dynamic multi-level perspective on system innovations (Geels, 2002a)

At the *landscape* level, changes usually take place slowly, e.g. cultural changes, demographic trends, broad political changes. The slowly evolving landscape developments are represented in figure 3 with fat long arrows. Landscape changes may put pressure on the regime.

At the *niche* level, actors in precarious networks work on radical innovations. Because a dominant design has not yet stabilized and there is much uncertainty, the efforts go in all kinds of directions, leading to variety. In figure 3, this is represented with small arrows going in different directions. Although radical innovations may seem promising for a while, there is no guarantee for success. Radical innovations may also gradually stabilize into a dominant design, represented in figure 3 with arrows growing longer and fatter.

The basic notion of Geels' improved multi-level perspective is that system innovations occur as the outcome of linkages between developments at multiple levels, represented with vertical dotted arrows. An important consequence of his addition is that the existing regime should not (only) be seen as a barrier for radical novelties, but the 'ongoing processes' in the regimes may also create opportunities. A system innovation occurs when the new innovation conquers wide market shares and links up with ongoing processes in the regime. Radical innovations break out of the niche-level when ongoing processes at the levels of regime and landscape create a 'window of opportunity'. These windows may be created by tensions in the socio-technical regime or by shifts in the landscape which put pressure on the regime. System innovations do not only involve technology and market shares but also changes on wider dimensions such as regulation, infrastructure, symbolic meaning, and industrial networks (represented by the increased density of arrows). Besides, system innovations are about the linking of *multiple* technologies. Once established, a new socio-technical regime may influence wider landscape developments (Geels, 2002a; Geels, 2005b).

An important aspect of the MLP is to do away with simple causality in system innovation. There is no 'cause' or driver of system innovation. Instead, there are simultaneous processes at multiple dimensions and levels. System innovations come about when these processes link up and reinforce one another. Such innovations are not simply 'caused' by novelties at the niche level, because their breakthrough and diffusion depends on processes and circumstances at the regime and landscape levels (Geels, 2005b).

This improved multi-level perspective of Geels will serve as a conceptual model for my research.

2.6 Promises and Expectations

Promises and expectations play a crucial role in early phases of technical change and in the creation of niches. In the early stages of development, the advantages of a new technology are often not evident. Its value still has to be proven (in terms of technical, social as well as commercial viability) and there are many resisting forces. In order to get the new technology on the agenda, actors make promises and raise expectations about new technologies. Promises are especially powerful if they are shared, credible (supported by facts and tests), specific (with respect to technological, economic and social aspects), and coupled to certain societal problems which the existing technology is generally not expected to be able to solve. Once certain promises have been accepted and placed on the agenda, activities need to be developed to substantiate the expectations, for example by conducting research or doing experiments (Kemp et al, 1998; Geels, 2002b).

Parties that promote and/or apply a technique do so because they believe that it will yield returns in the future, but they cannot be certain of these returns. They need testimony that their efforts are useful. The development of a technology is accompanied by attempts to convince others that the expectations are justified (Schot, 1998). Therefore these parties often construct and communicate positive expectations in order to make other actors believe that it will yield returns in future (Hoogma et al, 2005). This way expectations are used to attract attention and enroll more actors to widen the social network (Geels, 2005b) At first sight, it seems that this is happening with the 'hydrogen economy' as well. The hydrogen economy seems to be very popular in the U.S. and the current government is one of the proponents of it. As stated in the introduction, in his State of the Union Address of 2003 President Bush says:

"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car - producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom - so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation - to make our air significantly cleaner, and our country much less dependent on foreign sources of energy" (Bush, 2003).

Critics claim, however, that it will take much longer before the hydrogen economy will be realized or before mass production of FCVs will happen. Romm, one of the critics, speaks of "the hype about hydrogen" to indicate that the expectations about hydrogen are exaggerated. He claims that we need several technical breakthroughs to make it happen and that this will not happen the coming decades. We would do better to focus on renewables and other alternatives first, before we focus on hydrogen (Romm, 2004).

Because expectations and promises seem to be an important driver related to the hydrogen economy, and to technical change in general, I will pay special attention to it in my research. In this section I will therefore explain the dynamics of expectations in technological developments as a mode of coordination. This section is based on work of Van Lente and Rip (1998).

In sociology, several theoretical attempts have been made to fill the gap between functionalism which forgets creative actors, and an interactionism which forgets about constraining structure. Such attempts seek to overcome the dualism of structure versus agency. The key issues are how actions lead to structures, and how the structures enabling constraining action.

Technology dynamics teaches us that structure emerges and action is shaped in a way in which content matters as much as traditional sociological categories of explanation. Structures can be 'merely' prospective, and still be influential. To emphasize this, Van Lente and Rip introduce the term *prospective structure*.

Actions become coordinated through the prospect of a new technology and its functions while this emerging configuration is simultaneously shaping the technology to be. The coordination is actively sought by actors, but the patterns that may emerge cannot be attributed to any one particular actor. Phrased like this, a clear relation with the problematic duality of structure versus agency can be seen. Sociologists have taken (sometimes extreme) positions on the relative weight of structural arrangements versus the creative power of voluntaristic agents, and on the way structure influences or even determines agency, and vice versa. Technology dynamics, with their interest in change and the introduction of novelty, have something to offer in this problem.

The key issues regarding this problem become how actions lead to structures, and how the structure is enabling constraining action. Van Lente and Rip point out that expectations, and their related stories, about possible developments should be considered as a source of change in this discussion. These lead to action, not because there is a structure behind the backs of the actors, but because now actors are creating one before them. It is because of their content that these stories help to create new patterns and institutions. The basic mechanism is that actors position themselves and others (and future technology) in a story or plot, and so make others into characters in the story. Thus, prospective structures emerge, i.e. arrangements that do not yet exist, but are nonetheless forceful due to the perceived implications of the projected future.

Van Lente and Rip discuss three examples of emerging patterns in expectations about technology. In all three of them a co-evolution of structure and agency can be seen. First, Moore's Law as a self-fulfilling prophecy. Moore's Law is a prediction regarding the development of memory chips that became true. The fulfilling of this self-fulfilling prophecy did not occur because it is a prophecy, but because actors take up the prophecy and act accordingly. That is a basis for other actors to accept the expectations and act accordingly, etc.

Secondly, diffuse coordination and Membrane Technology. Based on expectations about Membrane Technology a gradual agenda was built and an independent and compelling macro-actor was established to coordinate the heterogeneous actors in the membrane technology field. This macro-actor mobilized rhetorical and other resources to further one's interests – but the interests were defined in terms of the promise of a new technology in which actors could and should participate. A promising technology itself can coordinate action – at least rhetorically in texts.

The third example of emerging patterns in expectations about technology is the self-justifying technology. Before 1985, High Definition Television (HDTV) was held to be a promising idea among technologists, but it was not widely promoted, certainly not as any kind of national cause, except perhaps in Japan. The shift to prominence after 1985 took place because HDTV became the subject of a strategic game. In the resulting tug-of-war around HDTV, more is at issue that interest politics around standards and markets. It is obvious that interest politics will occur: the economic and political interests associated with HDTV are immense. The potential world market is estimated in terms of hundreds of billions of dollars and the size of one's share of this market will have important consequences for other industrial activities, for the labor market, and for the relative strength of national economies. So it is not surprising when parties interested in the development try to gather support or try to promote this (future) commodity. Notable, however, is how interests are defined here. It is only because HDTV is taken as promising that there are interests at stake, and that interest politics can come into play. If HDTV were not seen as promising, there would be no interest in the technology, and thus no actor's interests to be staked out.

The promise of HDTV is not a black box promise: certain functions to be realized by the new TV system are emphasized, and these have rapidly turned into an agenda of requirements to be met by the new system. The dynamics of this process show a curious duality, which can be recognized in other cases well, and may be characteristic for how our technological culture works.

The dynamics of the self-justifying technology is a conversion of promises into requirements at the societal level. Once technical promises are shared, they demand action, and it appears necessary for technologists to develop them, and for others to support them. At the same time, the options which are considered feasible and promising are translated into requirements, guidelines and specifications. This shapes concrete design and development trajectories, now at meso and micro level, but also through conversion of expectations and promises.

Technological promises function as a yardstick for the present and as a signpost for the future. Technological determinism is not given, but actively constructed. The 'option-promise-requirement-necessity' sequence does not imply anything like an autonomous socio-technical process. The transitions do not occur automatically, but are the result of the actions and interactions of technologists, firms and governments. The transitions are a consequence of actors assessing what is "feasible", what is "obsolete", and what is "necessary", and of the efforts that follow these assessments. Moreover, the transitions are in principle reversible and can be undone – although entailing increasing costs and work. The pressure to at least recover and preferably to cash in on sunk investments also increases. As more and more is invested in a promising technology, any detour or even delay will encounter increasing resistance.

When some overall promise has been articulated and become forceful, the functions that were seen as necessary become specifications for design and development work. Promise-requirement cycles start up again, embedded in the overall framework. Behind the promise-requirement cycles lies the dynamics of expectations: as soon as expectations are shared they assume a life of their own. The basic point is that when expectations are shared they create a pattern into which the actors themselves may be locked. However, in and of themselves promises will not be sufficiently powerful to establish requirements for technology development. This demands that the promise is taken up in an agenda (a local, a field, or a macro agenda). While an expectation statement is performative, i.e. it does something, it is an action - and because of its script, others may react - it only becomes an issue that demands consideration and action when actions and reactions converge sufficiently for it to become part of an agenda.

Expectations and stories about the future in general, reduce essential contingency in a non-deterministic sense, by providing blueprints that can be used in action. Such stories are thereby transformed into reality. Starting with contingency, a scenario is told, presented, read, and filled in by the actions of self and others. This creates a structure, which becomes the background for further stories. Afterwards, some actors or factors may be identified as driving forces, but this is attribution, and part of the process. The process of filling in the scenario creates the substance from which structure as well as the agency, i.e. attributed actors, are derived.

Apparently, expectation statements contain a "script," indicating promising lines of research and technical development to be undertaken by the enunciator of the statement and/or by others. Thus, they mobilize support in specific ways. And they can be assessed as to their script, e.g., in discussions about priorities and strategic orientations in general. Because of their "scripts", expectations allocate roles for selves, others and (future) artifacts. When these roles are adopted, a new social order emerges on the basis of collective projections of the future. In this process mutual positioning of the actors takes place: firms position themselves in different ways.

2.7 Scripts

A final concept that plays a role in my research is the script of a technology. In the sociology of technology, it has been argued that artifacts and technologies contain an intended use. This is referred to as the script of a technology or artifact. This script prescribes (in a more or less coercive manner) what users have to do (or not to do) to produce the envisioned functioning of the technological artifact (Oost, 2003). Usually developers of technical objects 'inscribe' their vision of their defined actors and future use in the technical content of the new object (Akrich, 1992). The power of this script is limited though; real users can behave differently than the projected user and use the artifact in a different way than the script prescribes. An example of this is the screwdriver. The intended use of a screwdriver is to screw of unscrew screws. In reality, however, we see many other different uses. Users use the screwdriver for stirring their coffee for example, or to open up a beer bottle. The process in which new meanings are given to artifacts by users is called de-scription by Akrich (1992)

Artifacts and technologies can also contain scripts that are not based on the developers vision, but that are based on the nature of a technology. A large containership, for example, is made for navigating the ocean and is not suitable for navigating small rivers. The script, thus, limits certain kinds of usage. Scripts that are based on the nature of a technology are much more powerful and harder to change. It is these scripts that are of importance to the hydrogen transition. The different hydrogen technologies have their own script, which can have a different impact on the transition and on our society. This will be discussed in chapter 4.

2.8 Conceptual Model

Summarizing the previous section, for my research I will make use of the System Innovations approach, which relies on SST and co-evolutionary theories, and the multi-level perspective that distinguishes three levels (the micro level of technological niches, the meso level of technological regimes and the macro level of socio-technical landscapes) will serve as a conceptual model. The dynamics of this MLP are shown in figure 3 and these will play an important role. Within this model, special attention will be paid to expectations and promises.

For my actual CTA I made use of the four steps model developed by Smit and Oost (1999). Their model is a useful tool for a systematic and comprehensive analysis of the technology, its consequences and social judgments, in order to give steering, control and policy options. The multi-level perspective as well as expectations and promises and scripts are integrated in the 4-step model and formed the input for the questions that will be addressed in each step. The four steps of the model are:

1. *Exploration of the technology and a foresight of the technological developments*

   In this step the hydrogen technology will be explored. The most important aspects of the technology will be discussed as well as the developments over time and the current developments and applications. Based on experts' visions the expectations and promises of the different aspects will be outlined, which will lead to the discussion of likely infrastructures for the future hydrogen economy. The questions that will be discussed are:

a) What are likely infrastructures for the future hydrogen economy?
b) What changes on the landscape level influence the regime level and create opportunities for new technologies?
c) What new technologies put pressure on the regime level?
d) What processes in niches influence the regime level?
e) Which co-evolutionary processes have occurred?
f) How do expectations and promises influence the developments?
g) What role do scripts play in the technological development?

2. *Assessment of possible social/environmental impacts and actor groups involved*

The second step of the CTA will analyze the different relevant organizations, institutes, societal groups, etc. that play a role in the hydrogen transition. Four different actor groups will be distinguished: technology regulators; technology developers; technology users; and other groups. The focus in this step is especially on the positions, interests and opinions of each actor (group) and how they influence the developments. The questions that will be discussed are:

a) How do new actors try to put pressure on the existing regime?
b) How does the existing regime influence and control the developments and policies?
c) What articulation processes related to promises and expectations have occurred?
d) What role do social mechanisms play?
e) What is the role of users in the developments?
f) What role do technological nexuses play?

3. *A normative assessment of the impacts from the perspectives of involved actor groups, and an analysis and evaluation of this assessment.*

Based on the previous two steps, first the impacts that will come with the prospective transition path will be discussed in this step. This will be followed by an analysis of how the involved actors assess the possible social impacts. The opinions of the actors about the desirability of the several impacts will be discussed and the normative principles, related to the American culture, that form the basis for these assessments are evaluated. For this step the Multi-Level Perspective (MLP) as described in the previous chapter seems not to be useful. The MLP only focuses on the nature of technological change, but does not involve an assessment of this change. This step is therefore not particularly linked to concepts from the MLP. The questions that will be discussed are:

a) What impacts are likely to come with the prospective transition path?
b) How do actors assess the developments and (social) impacts of the prospective transition path?
c) What normative principles form the basis for these assessments?

4. *Feedback*

The first three steps of the CTA lead to the final step, the feedback. The feedback is aimed at reducing undesirable or controversial impacts and stimulating desirable ones. For this feedback the MLP forms an input again. The feedback considers both actions that can be taken related to the technological developments at the micro-level as decision-oriented actions, policies and societal influences that put pressure on the regime level and causes changes at the landscape level. The feedback can provide valuable inputs to decision and policy makers, managers, R&D departments, etc. The questions that will be discussed are:

a) In what way are the developments controllable or steerable and who can do it?
b) What actions can be taken at the different levels of the MLP?
c) What co-evolutionary processes are important to consider?

3. Methodology

This chapter describes the methodology I have used to do my analysis, to gather my data and to write my report.

3.1 Literature Review

First of all an extensive literature review was performed to gather relevant information about the topic, to learn from recent studies and to find out about the key issues and problems related to the technology and the gaps in literature. After I had a clear understanding of the things that were at stake I narrowed my focus and started to gather relevant empirical data.

3.2 Data

The kind of data that seemed to be important followed from the conceptual model, as discussed in Chapter 2. Since this research deals with technology foresights, no data about this future is of course available. In order to be able to say something sensible about the future of hydrogen as a fuel and its environment, data about expectations and the dynamics of the technology, and the several aspects that influence these, are therefore important.

First of all data about the (infrastructural) technology and hydrogen itself are needed. The main sources of (empirical) information for the first part of the CTA were scientific (specialist) literature and Internet sources. In addition, information from the field, gathered by interviews, was used to figure out likely futures for the hydrogen economy.

For the second step, information about the social structures related to transportation and energy supply systems has been gathered and analyzed. This was mainly information about the main actors in both fields, about policies, about power relations, etc. Literature, the internet, policy documents, hearings in Congress, governmental programs, etc. served as a source for that. Besides, a lot of information was gathered by interviews.

Based on the gathered information and the gained knowledge, insights about likely, *expected* future hydrogen infrastructures became clear. This served as an input for the impact analysis and for the normative assessment of the impacts.

For my research I have interviewed 15 different actors in the hydrogen field. Four of them were from big energy companies, two were working for the government, three were scientists at universities, four were working for associations or societies involved in the hydrogen debate, one was from an environmental organization and one was working for a Research and Consultancy company. Table 1 shows an overview of the interviewees.

Table 1: Overview interviewees

Organization	***Name***	***Function***
Energy Companies		
BP	Maria Curry-Nkansah	Hydrogen Project Manager
Chevron/Texaco	Jim Stevens	Catalyst Program Manager, Chevron Technology Ventures
Chevron/Texaco	Rick Zalesky	Vice President Hydrogen Business, Chevron Technology Ventures
General Atomics	Kenneth Schultz	Director of Operations
Government		
DOE	Tina Kaarsberg	Acting Director, Office of International Energy Markets
Senator Dorgan's Office	Mark Fraase	Staff Member Department Energy and Natural Resources
Universities/Research Institutes		
Georgia Tech Research Institute	Gary Gray	Senior Research Engineer
Georgia Institute of Technology	Douglas Noonan	Professor Environmental Economy
University of California, Davis	Daniel Sperling	Professor Civil Engineering and Environmental Science and Policy
Associations		
National Hydrogen Association	Patrick Serfass	Director Program and Technology Development
NHA	Debbi Smith	Executive Vice President
American Solar Energy Society	Ron Larson	Board of Directors, Executive Committee, Chair
American Wind Energy Association	Norie Flowers	Assistant to the Executive Director
Environmental Organization		
Environmental Defense	Bill Chameides	Chief scientist
Research and Consultancy		
WinterGreen Research	Susan Eutis	President

Since most actors were not situated in or near Atlanta my interviews were mainly phone interviews. By using semi-structured interviews I have gathered relevant information about the hydrogen transition, about actors' expectations regarding the technology, about social mechanism, about the impacts, etc. In appendix A an overview of the kind of questions I used is given.

3.3 Scope

A few more remarks regarding my research, and especially regarding the scope of my research, have to be made. First, although environmental changes and, to a certain degree, 'peak oil' are global concerns and these issues are on the agendas worldwide, I focused my research especially on the U.S. If necessary I took a look at activities and process in other countries, but that was not the main focus. The U.S. is interesting regarding hydrogen and energy for three reasons: a) with only 5% of the world population, the U.S. consume 25% of the world energy, b) the 'hydrogen economy' is very popular in the U.S. and a lot of research is done here, and c) global governance reflects an overarching U.S. influence and the U.S. can thus have a great influence on setting standards and policies.

Secondly, although it might be interesting and important to analyze the whole spectrum of projects in the technological field of sustainable transportation and energy, I, because of the nature and the time limits of this research, only focused on hydrogen possibilities and left other alternatives like electric and hybrid vehicles out. I also did not analyze different sustainable energy systems (wind, solar, hydro) in depth. Moreover, regarding hydrogen itself, I only focused on hydrogen related to the transportation system (which is seen as the most demanding sector in the future) and not related to other applications.

Finally, although many technology assessments and scenarios focus on a time period of up to 50 years, my main focus is on a time period of a few decades. With growing energy demand and fossil fuel use (especially in Asia) environmental problems are getting worse fast and the 'end of cheap oil' might reach us sooner than we think, maybe even at the end of this decade already. It is therefore important to analyze what needs to be done to have a solution for these problems within a relatively short time span and not in the far future. Moreover, it is hard to say anything sensible regarding the long term future.

4. Exploration of the Technological Developments

Hydrogen has several characteristics that make it a very promising fuel for the future and many technologies are being developed to make hydrogen the fuel of the future. These new technologies, which are developed in technological niches, have the potential to form a new technological regime and substitute the existing petroleum regime. From the multi-level perspective, discussed in chapter 2, it became clear that the development of new technologies is influenced by changes or tensions at the landscape and regime level. Such changes play an important role in the hydrogen transition as well, and will be discussed in this chapter. Apart from influencing the niches, the changes and tensions at the landscape and regime level put, like the niches, a lot of pressure on the petroleum regime. In the hydrogen transition process co-evolutionary processes play an important role. The many variations are developed based on the existing and anticipated future selection environments and, as we will see in the next chapter, the variations influence the selection environment as well. Within this process expectations about promising technologies and the future selection environment play a crucial role and have a great influence on the developments and on the petroleum regime.

In section 4.1 I will first describe the characteristics of hydrogen that make it a promising fuel, the interests in hydrogen as a fuel over time, and the current use of hydrogen in industries. After that the aspects that put pressure on the existing petroleum regime will be explored in section 4.2 (landscape and regime level) and section 4.3 (technological developments). In section 4.3 co-evolutionary processes – the processes of variation and selection, and path dependency – and the role of scripts will get special attention. The influence of expectations and promises on the technological developments will also be analyzed. Section 4.3 ends with a summary of the technologies and of likely infrastructures for the future hydrogen economy.

4.1 Hydrogen

To get a better understanding of the importance and the (future) role of hydrogen, this section gives an overview of the characteristics of hydrogen that make hydrogen a promising technology for the future, the interests in hydrogen as a fuel over time, and the current use of hydrogen in industries.

4.1.1 Hydrogen Characteristics

Hydrogen is the simplest element and most abundant gas in the universe. Each hydrogen molecule has two atoms of hydrogen. Hydrogen is the lightest element, yet it has the highest energy content per unit weight of all the fuels – three times higher than gasoline. When harnessed as a form of energy, it becomes “the forever fuel” (Rifkin, 2002). It never runs out, and, because it contains not a single carbon atom, it emits no carbon dioxide and no other greenhouse gases and pollutants as well; when used as a fuel for vehicles the only by products are water and heat. Hydrogen therefore has the potential to be a clean fuel and can become a substitute for fossil fuels in the future. Hydrogen is found everywhere on earth, in water, fossil fuels, and all living things. Yet, it rarely occurs naturally in large quantities or high concentrations on earth. Instead, it has to be extracted from natural sources, such as fossil fuels, biomass, or water and is therefore considered an energy carrier like electricity. The fact that it can be produced from a variety of (domestic) energy sources makes hydrogen an even more interesting fuel. It offers significant diversity and means the U.S. would not be dependent upon a small number of suppliers. Moreover, there is (theoretically) potential for producing domestically all of the hydrogen used in the United States.

4.1.2. Interest in Hydrogen

Although the 'Hydrogen Economy' is getting more and more popular, hydrogen is not a new product, recently developed. Hydrogen was first discovered by the British scientists Henry Cavendish. In a paper delivered before the Royal Society of London in 1776, he reported on an experiment in which he had produced water by combining oxygen and hydrogen with the aid of an electrical spark. Since the elements had not yet been named, he called one "life-sustaining air" and the other "inflammable air." the French chemist Antoine Laurent Lavoisier successfully repeated Cavendish's experiment in 1785 and called the "life-sustaining air" oxygen and the "in flammable air" hydrogen (Rifkin, 2002).

The first practical use of hydrogen, not surprisingly, was in warfare and was used in reconnaissance balloons. The first hydrogen generator was built at an army camp just outside Paris in 1794 (Rifkin, 2002). As far back as 1874, during the foulest days of the Industrial Revolution, Jules Verne envisioned a world based not on fossil fuels but on clean hydrogen energy: " water will be the coal of the future" (Vaitheeswaran, 2003)

Hydrogen was been commercially produced in the 1920s in Europe and North America. In 1923, John Burden Sanderson Haldane, the first scientist of note to envision the full potential of hydrogen, predicted that hydrogen energy would be the fuel of the future. His notion was so revolutionary at the time that it was met with incredulity by his peers within the academy. Yet, in its every particular, his thesis was tantamount to a working blueprint of how hydrogen would later be harnessed and exploited. According to Haldane the great social advantage of adopting a hydrogen energy regime is that "energy will be as cheap in one part of the country as another, so that industry will be greatly decentralized" (Rifkin, 2002).

Hydrogen was first exploited as a fuel in aviation in the 1920s and 30s. German engineers used it as a booster fuel in the Zeppelins. By the 1930s and '40s, hydrogen was being used in Germany and England as an experimental fuel for automobiles, trucks, locomotives, and even submarines and trackless torpedoes (Rifkin, 2002).

However, while hydrogen has been widely used in the refining process as a feedstock and raw material for the production of a range of products, its value as a fuel was largely ignored in the post-World War II era, despite the early experimental successes in the 1920s and 30s. It was not until the oil crisis in 1973 that scientists, engineers, and policymakers decided to take second look at hydrogen as an all-purpose form of energy. In the years that followed, the U.S. and other governments began to advance small amounts of public funds in hydrogen research. The U.S. program never exceeded $24 million. The European Economic Community spent between $72 million and $84 million in hydrogen research in the 1970s. As the energy crisis waned and the price of oil began to drop began on world markets in the 1980s, government funding for hydrogen research declined significantly (Rifkin, 2002).

Interest in hydrogen began to pick up again in the 1990s after the publication of alarming studies and reports warning that increased carbon dioxide emissions from the burning of fossil fuels was heating up the planet and posing a potentially grave threat to the earth's biosphere. A growing number of scientists began to raise the possibility of making the transition from hydrocarbon fuels to hydrogen as a way to address the problem of global warming. Meanwhile, experimental research, both in academia and the commercial sector, began to lay the technical foundation for a hydrogen future (Rifkin, 2002).

According to Debbi Smith, Executive Vice President of the National Hydrogen Association (NHA), during the Reagan administration R&D focused on hydrogen continued on a small scale in national laboratories and at universities. During this period Smith was working for the Reagan administration and it was not before the Clinton administration that the interest for hydrogen was growing again. R&D became more applied and industries got involved in governmental projects. However, there were no alliances yet. During the first Bush administration (2000-2004) public private alliances were formed with the automobile industry, under the name FreedomCAR, to which I will come back in the next chapter. Later on, energy companies got involved in this collaboration as well. They work together on the so-called 'chicken-egg problem', which is the problem of investing in an infrastructure while the demand for hydrogen is still low and vice versa; investing in fuel cell vehicles while there is no infrastructure. In 2003 President Bush announced the Hydrogen Initiative which, according to Smith, was an important step, because the hydrogen transition issue is too big for industries only. Government support is needed. Since then, interest in hydrogen as a fuel rose significantly.[4]

It is worth noting that General Motors, the largest automaker in the world, was the first to use the phrase "the hydrogen economy." That was back in 1970, when GM engineers began to look at hydrogen as the possible energy fuel of the future. Thirty years later, after many trailblazing efforts had begun to establish the viability of a hydrogen future, GM's Executive Director of Advanced Technology Vehicles, Robert Purcell, speaking at the annual meeting of the National Petrochemical and Refiners Association in May 2000, told the members that "our long-term vision is of a hydrogen economy" (Rifkin, 2002).

4.1.3. Current Use of Hydrogen

In the industrial sector hydrogen has been used on a large scale for decades. At present hydrogen is one of the basic materials used by the chemical and petrochemical industry. Hydrogen is produced and used in refineries, and it is widely used for the synthesis of chemical raw materials (production of ammonia, ethylene and methanol). Hydrogen is also used in smaller quantities in other sectors such as welding, electronics, the steel and glass industry and food processing (Alleau; 2003; Plugpower, 2003; ISO/TC, 2004)

Today's world production of hydrogen is approximately 40-50 Mt/y (Plugpower, 2003; Simbolotti, 2004; Di Cecca, 2004; ISO/TC, 2004), which, expressed in energy equivalents, represent only 1 - 2% of the world total primary energy supply (TPES) (Alleau, 2003; IEA, 2003; Simbolotti, 2004; Di Cecca, 2004). The most important part of this hydrogen is a sub-product of other processes used by the industrial sites at stake and

[4] Data from interview with Debbi Smith, NHA

the production of hydrogen from special units corresponds to less than 0.1% of the world energy consumption (Alleau, 2003).

The hydrogen demand around the world varies by region. North America is the major user (79%) followed by Europe (14 %) and Asia (7%) (ISO/TC, 2004). In the US, for example, about 20 billion cubic meters of gaseous hydrogen is produced annually (compared to US production of about 550 billion cubic meters of natural gas) (IEA, 2003). Figure 5 shows the hydrogen demand worldwide.[5]

As shown in figure 4, about 95 percent of hydrogen made on a large scale in 1999 was from fossil primary resources and about 48 percent of hydrogen globally was made from natural gas. In the United States, over 90 percent of hydrogen is currently derived from natural gas (Ogden, 2004).

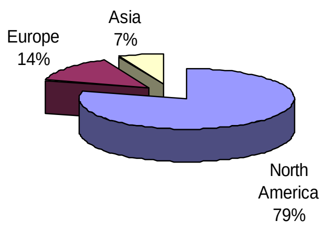

Figure 5: Hydrogen Demand around the World

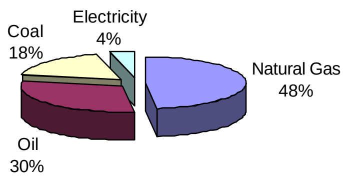

Figure 4: Hydrogen Production by Source

The largest part – over 90% – of the hydrogen produced in the world is used 'captive'; industrial facilities often build their own hydrogen production unit nearby to ensure its supply. This hydrogen is used in ammonia, methanol, chemicals & refineries industries (Plugpower, 2003). With less than 10%, merchant hydrogen is a minor market (Plugpower, 2003), and is delivered primarily in gaseous form (ISO/TC, 2004). This hydrogen is used for refining, chemicals, metals, electronics (Plugpower, 2003).

The hydrogen demand varies with the type of applications. Hydrogen is primarily used in the chemical industry (72 %), more specifically in petroleum refining (32 %), ammonia manufacturing (30 %) and the synthesis of methanol (10 %) (ISO/TC, 2004). The rest of the hydrogen demand is from small-volume consumers, see figure 6.

[5] The Middle East and South America have the potential for producing large quantities of hydrogen from hydroelectricity and refineries. They could also use large volumes of hydrogen. However, available statistics do not provide information with regard to these regions (ISO/TC, 2004).

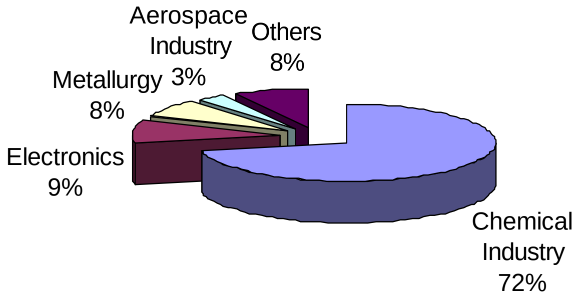

Figure 6: Consumption of Hydrogen by type of applications in 1990 (ISO/TC, 2004)

Most of the world hydrogen consumption is produced by the consumer at the site where it will be used. Therefore, the largest consumers, i.e. the refineries and the manufacturing plants of ammonia and methanol, are also the largest producers of hydrogen. They not only produce hydrogen for their own needs, they also supply hydrogen to small-volume consumers. Hydrogen is also inevitably produced from the production of chlorine. As a result, the chemical and petrochemical industries currently produce about 98 % of merchant hydrogen (ISO/TC, 2004). In figure 7 the different hydrogen facilities situated in the United States are shown.

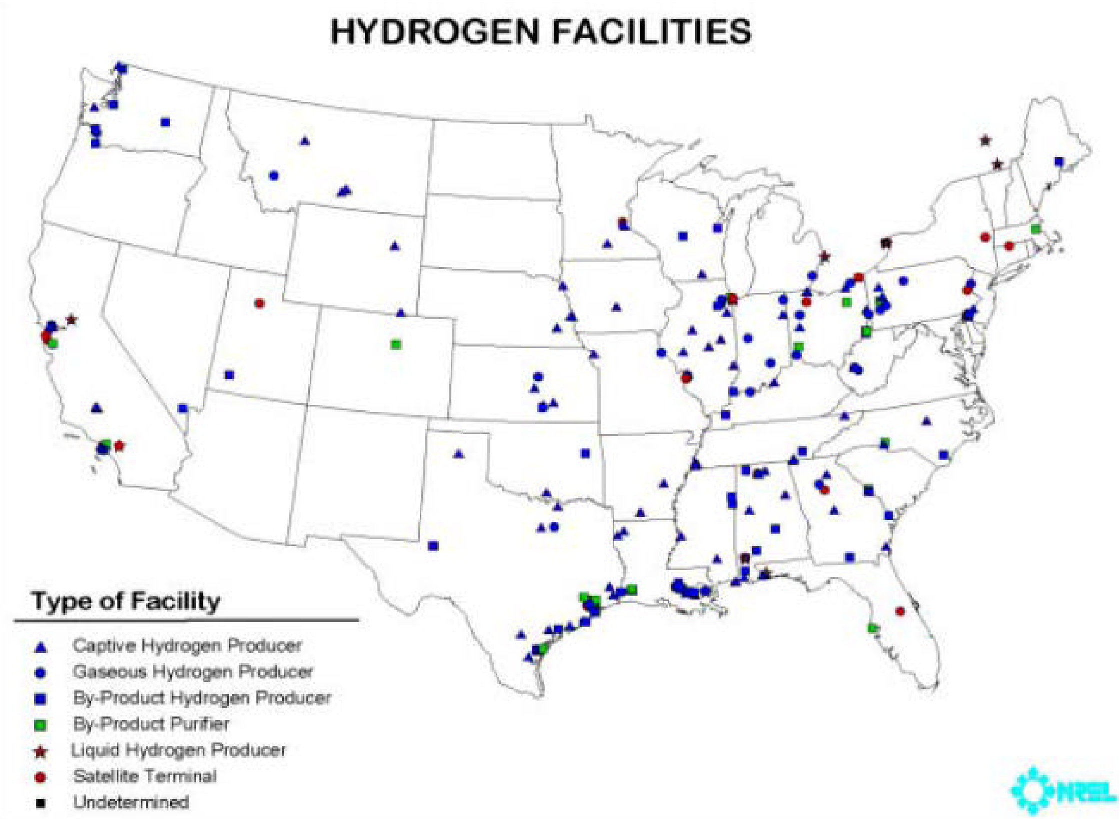

Figure 7: Hydrogen Facilities (Source: Plugpower, 2003)

Today hydrogen is still mainly considered as a chemical and not as an energy factor, except for space propulsion which represents a very small part (Alleau, 2003), as can be seen in figure 6. From a survey conducted by the Energy Statistics Division of the International Energy Agency (Di Cecca, 2004) on hydrogen it appears that collecting information on the production and use of hydrogen as *an energy-carrier* is premature in most countries. From the 15 countries that responded to their survey, only 2 countries indicated collecting hydrogen statistics on a regular basis (Di Cecca, 2004). Thus, statistics are not available.

Apart from the aerospace industry, the use of hydrogen as an energy carrier is currently limited to R&D and demonstration projects (Di Cecca, 2004), since most of the technologies that are required to implement the hydrogen energy system (like fuel cells) are still in their development and demonstration phase. As they have not reached commercialization yet, no available statistics cover these applications (ISO/TC, 2004). In the transportation sector hydrogen is, next to the direct use in space shuttle programs and in demo H_2 ICE and fuel cell vehicles, also used indirectly in refined products and as blended fuel, CNG+H_2 (Plugpower, 2003).

Its abundance, cleanliness and the variety of energy sources that can be used to produce it, make hydrogen a promising fuel for the future. Hydrogen has already been used at a large scale in industries, but mainly as a chemical factor and not as an energy carrier. Despite some early experimental successes with hydrogen as a fuel in the 1920s and 30s, it was not until the 70s and later the 90s that interests in hydrogen as a fuel rose significantly. In the next section I will further explore the causes of the increasing interests these days; the changes at the landscape and regime level.

4.2 External and Internal Pressure on Regime

In the previous section we saw that interest in hydrogen as a fuel rose significantly in the 70s during the oil crisis, decreased again after the oil crisis and then in the 90s interest rose again, but this time because of environmental reasons. Both the oil crisis and the growing concern for global warming put pressure on the petroleum regime, the regime that plays a key role in my analysis. In the U.S., and in most other developed countries, three important aspects that put pressure on the petroleum regime can be seen today. These are environment, peak-oil, and geopolitics and are explored in this section. These issues put pressure on the regime from both the landscape level, as from within the regime itself. The pressures influence the development of technologies embedded in regime as well as new promising alternatives by creating ‘windows of opportunities’ for new technologies, which will be discussed in section 4.3. A demand for alternative fuels was created and hydrogen became as popular as it is these days in the U.S., and worldwide.

4.2.1 Environment

The increase in environmental concern that we have seen since the 90s, is a change at the landscape level; it forms a structural trend external to the regime. This trend does not only relate to the petroleum regime and cannot be changed at will by the regime actors.

Regarding environmental issues, the two main concerns in relation to fossil fuels and transportation systems are climate change and air quality. The fossil fuel era had, and still has, a significant influence on both, according to most scientists. For the 10,000 years leading up to the Industrial Age, the balance of greenhouse gases was relatively stable, so that the temperature on the planet remained within a narrow range. The burning of massive amounts of coal, then oil and natural gas in the 19th and 20th centuries changed this equation (Rifkin, 2002).

The heating up of the earth is the result of a growing accumulation of gases in the atmosphere that are blocking heat from escaping the planet. This "greenhouse" phenomenon begins when solar radiation enters the earth's atmosphere, hits the surface of the earth, and is transformed into infrared energy and heat. The heat rises and bombards carbon dioxide and other gases in the earth's atmosphere, forcing the gaseous molecules to vibrate. The gas molecules act as reflectors, sending some of the heat back to the surface, creating a warming effect. Carbon dioxide, methane, and other greenhouse gases provide an atmospheric blanket that allows enough of the heat generated by the sun's radiation to stay on earth to provide the right conditions for the flourishing of life (Rifkin, 2002).

The carbon dioxide content in the atmosphere today is approximately 31% greater than it was in 1750, at the onset of the fossil fuel era. That concentration, according to the U.N. Intergovernmental Panel on Climate Change, has not been exceeded in the past 420.000 years and likely not in the last 20 million years. The rate of increase in carbon dioxide concentration, according to the panel, is without precedent in the past 20.000 years. Nearly 75 percent of the increase in carbon dioxide concentrations in the past 20 years is attributable to the burning of fossil fuels. The remainder is the result of deforestation and land use changes, both of which release carbon dioxide into the atmosphere. While the land and ocean absorb half of the increase in carbon dioxide emissions, the rest migrates to the atmosphere (IPCC, 2001; Rifkin, 2002).

In figure 8, the annual CO_2 emissions in the U.S. are shown from 1949-2004. The per capita CO_2 emissions in the U.S. in 2000 were about 19.5 metric tonnes. Compared to Japan and Germany, this was twice as high. It was three times higher than France and compared to Chad, this was more than 1,400 times higher (World Resources Institute, 2003).

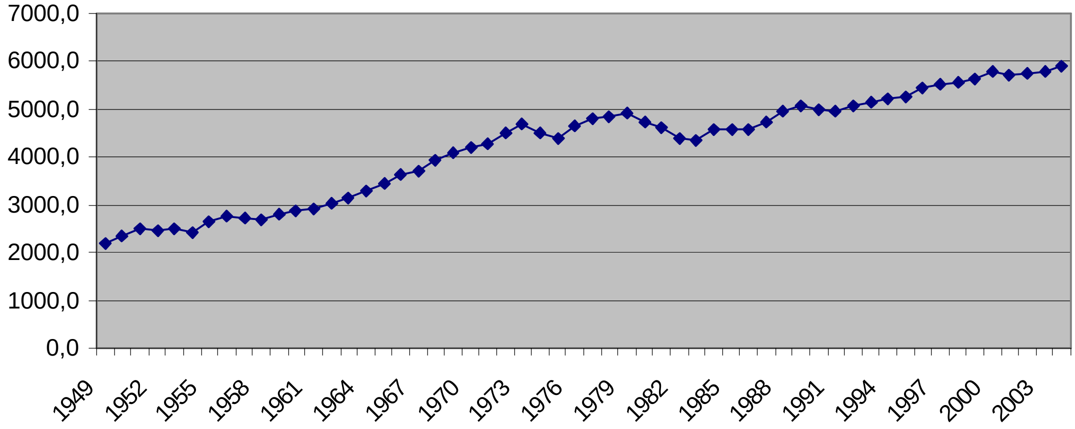

Figure 8: Total Energy-Related Carbon Dioxide Emissions in the U.S. (Million Metric Tons of Carbon Dioxide) (EIA, 2005d).

The increase in carbon dioxide is responsible for more than 70 percent of the global warming effects, while methane makes up 24 percent and nitrous oxide only 6 percent of the effects (Rifkin, 2002). The IPCC scientists say that the global average surface temperature increased by 1.08 ± 0.36 ºF over the course of the 20th century. Moreover, the increase is likely to have been the largest during any century in the past thousand years. And, according to the scientists' computer models, the global average surface temperature is forecast to increase by between 2.52 and 10.44 ºF by the year 2100 (IPCC, 2001; Rifkin, 2002).

This forecast could have devastating long-term effects on the earth's ecosystems, including the melting of glaciers and the Arctic polar cap, a rise in sea water levels, increased precipitation and storms and more violent weather patterns, destabilization and loss of habitats, northward migration of ecosystems, contamination of freshwater by saltwater, massive forest die back, accelerated species extinction, and increased droughts. The IPCC report also warns of adverse impacts on human settlements, including the submerging of island nations and low-lying countries, diminishing crop yields, and the spread of tropical diseases northward into previously temperate zones.

The emission of greenhouse gases and pollutants forms a serious threat for air quality and with that for the health of human, plant, and animal life. In the U.S. especially California became well-known for its problems and since the beginning of the 20th century it is fighting air pollution and smog. The main problem with air quality and smog is ozone. Ozone is formed by a, sunlight driven, photochemical reaction between the exhausts of automobiles, refineries, power plants, etc. (AQMD, 1997).

California has actively tried to reduce air pollution and increase air quality. On October 14, 1947, the Los Angeles County Board of Supervisors established the nation's first air pollution control program by creating the Los Angeles County Air Pollution Control District. Thirty years later the South Coast Air Quality Management District (AQMD) was formed. Because of regulations, new technologies, stimulation of transit systems, ozone levels have decreased by almost a factor 3 between 1955, when modern monitoring began, and 1996 (AQMD, 1997). Air quality problems are still urgent though in many cities in the U.S., but even more worldwide.

4.2.2 Peak-Oil

Energy, oil and transportation play a key role in the American economy and society. With only 5% of the world population, the U.S. consumes 25% of the world's energy. In 2004 transportation counted for 28% of the total energy consumption in the U.S. (EIA, 2005a). The total oil consumption is about 15.5 million barrels per day (Mbl/day) of which over 10 Mbl/day are imported with Canada, Saudi Arabia, Mexico, Venezuela, Nigeria and Iraq as the main suppliers. Oil consumption for transportation is almost 14 Mbl/day. By the end of 2004 and there were over 243 million registered vehicles in the U.S. (BTS, 2006). The total amount of miles driven in the U.S. in 2004 by all vehicles was almost 3 trillion miles. Per capita that is about 10,000 miles and the per capita oil consumption for transportation in the U.S. is about 17 barrels a year, which is over 700 gallons (BTS, 2006). Compared to Japan, this is 1.5 times more and compared to Germany even twice as much (CIA, 2006). These figures show the importance of oil (and transportation) to the American society and, as President Bush stated in his State of the Union Address of 2006 (Bush, 2006), it indeed seems that the U.S. is addicted to (foreign) oil.

In 1973 and 1979 a pair of sudden price increases rudely awakened the industrial world to its dependence on cheap crude oil. First prices tripled in response to an Arab embargo and then nearly doubled again when Iran dethroned its Shah, sending the major economies sputtering into recession. Many analysts warned that these crises proved that the world would soon run out of oil. Yet they were wrong (Campbell and Laherrere, 1998).

Their dire predictions were emotional and political reactions; even at the time, oil experts knew that they had no scientific basis. Just a few years earlier oil explorers had discovered enormous new oil provinces on the North Slope of Alaska and below the North Sea off the coast of Europe. By 1973 the world had consumed, according to many experts' best estimates, only about one eight of its endowment of readily accessible crude oil. The five Middle Eastern members of the Organizational Petroleum Exporting Countries (OPEC) were able to hike prices not because oil was growing scarce but because they had managed to corner 36 percent of the market. Later, when demand sagged, and the flow of fresh Alaskan and North Sea oil weakened OPEC's economic stranglehold, prices collapsed (Campbell and Laherrere, 1998).

According Campbell and Laherrere, the next oil crunch will not be so temporary. Their influential analysis of the discovery and production of oil fields around the world suggests that within the current decade, the supply of conventional oil will be unable to keep up with demand. According to their calculations, the world had at the end of 1996 approximately 850 billion barrels of conventional oil (Gbo) in P50 reserves[6]. This conclusion contradicts the picture one gets from oil industry reports, which boasted of 1,020 Gbo in "prove" reserves at the start of 1998 (Campbell and Laherrere, 1998). In figure 9 BP's prediction of proved oil reserves at the end of 2004 are shown. These numbers are indeed higher than the numbers of Campbell and Laherrere.

[6] The P50 value is the number of barrels of oil that are as likely as not to come out of a well during his lifetime, assuming prices remained within a limited range.

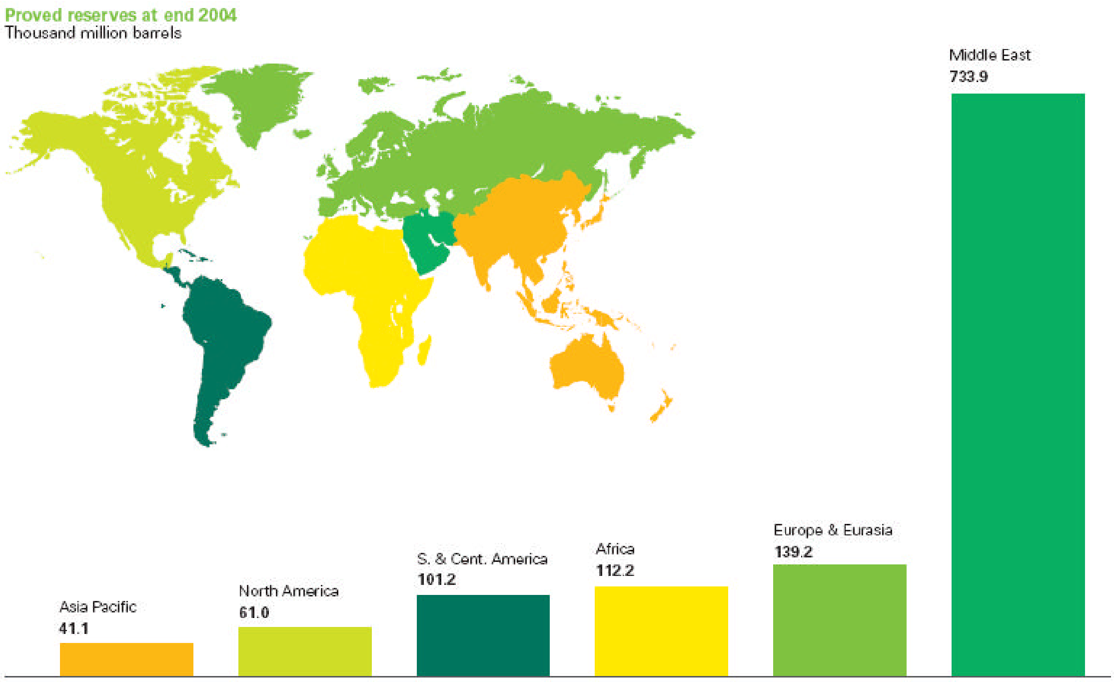

Figure 9: Proved oil reserves at end 2004 (BP Statistics, 2005)

Although different estimates of the existing oil reserves differ a lot from each other and different methods to make predictions about when oil will peak are used, oil is expected to peak within one or two decades[7]. This does not mean that the world is running out of oil – at least not yet. What our society does face, and soon, is the end of the abundant and cheap oil on which all the industrial nations depend (Campbell and Laherrere, 1998). How high prices go will be determined by a number of variables. First, according to the IEA forecast, the five swing producers in the Middle East – Saudi Arabia, Iraq, Iran, Kuwait and the United Arab Emirates – would need to increase oil production from 27 million to 48 million barrels per day between now and 2010 to meet increasing global oil demands. However, currently planned expansion in oil production in the Middle East is likely to fall short of what is needed by some 10 million barrels per day, leaving a dangerous shortfall in oil production that could significantly increase the price per barrel on world markets. Second, even the current expansion plans – which are too little to meet expected demand – will be so expensive that they will likely drive the price per barrel even higher, well before oil production peaks in the Middle East (Rifkin, 2002).

One way or another, say a growing number of geologists and industry analysts, the price of oil on global markets is going to go up, and probably much sooner than most people expect (Rifkin, 2002). The warning signs are everywhere; between January and May 2006 the price of a gallon of gasoline in Atlanta rose from about $2.30 till more than $3, an increase of over 30%. From an economic perspective, when the world runs completely out of oil is thus not directly relevant: what matters is when production begins to taper off (Campbell and Laherrere, 1998).

[7] ."Peak" is believed to occur when about half of the estimated ultimately recoverable reserves of oil in the world have been produced.

Peak-oil is a problem that can be seen as an internal problem of the petroleum regime. As we have seen, 90% of the total oil consumption in the U.S. is used for transportation. Peak-oil is a result of the existing regime and will affect this regime as well. Therefore peak-oil puts an internal pressure on the petroleum regime from within the regime. Peak-oil also has its effect on the landscape level though. Oil is a very important factor for the American economy, and, as mentioned in chapter 2, economic growth and oil prices form the content of socio-technical landscapes.

4.2.3 Geopolitics

Apart from environmental concern, another change at the landscape level is the current geopolitical concern. The tensions in the Middle East, the growing Muslim population, 9/11, the continuous threat of terrorists' attacks, etc. have increased an anxiety regarding power relations in the world. This has an influence on the petroleum regime and caused internal regime pressure, since the bulk of the oil imports in the U.S. come from the Middle East.

While the experts disagree about when global oil production is likely to peak, they agree that when it does, virtually all of the remaining untapped reserves will be left in the Muslim countries of the Middle East, potentially changing the current power balance in the world (Rifkin, 2002). Energy dependence is higher today than it was during the "oil shock" of the 1970s, and oil imports are projected to increase. In the U.S., passenger vehicles alone consume 6 million barrels of oil every single day, equivalent to 85 percent of oil imports. If just 20 percent of cars used fuel cells, oil imports could be cut by 1.5 million barrels every day[8].

Western countries are dependent on oil and therefore on the oil producing countries in the Middle East which have two third of the world total oil supplies, as can be seen in figure 9. Especially Saudi Arabia with 25% and Iraq with 10% have a lot of influence[9]. In addition to oil reserves, natural gas reserves are also mainly situated in the Middle East, as is shown in figure 10.

[8] http://www.fuelcells.org/basics/benefits.html
[9] http://www.e21.nl/nu_page.cgi?l=%2Fsite2001%2Fstorylines%2F000003&v=C&i=%2Fsite2001%2Fitems%2F000311

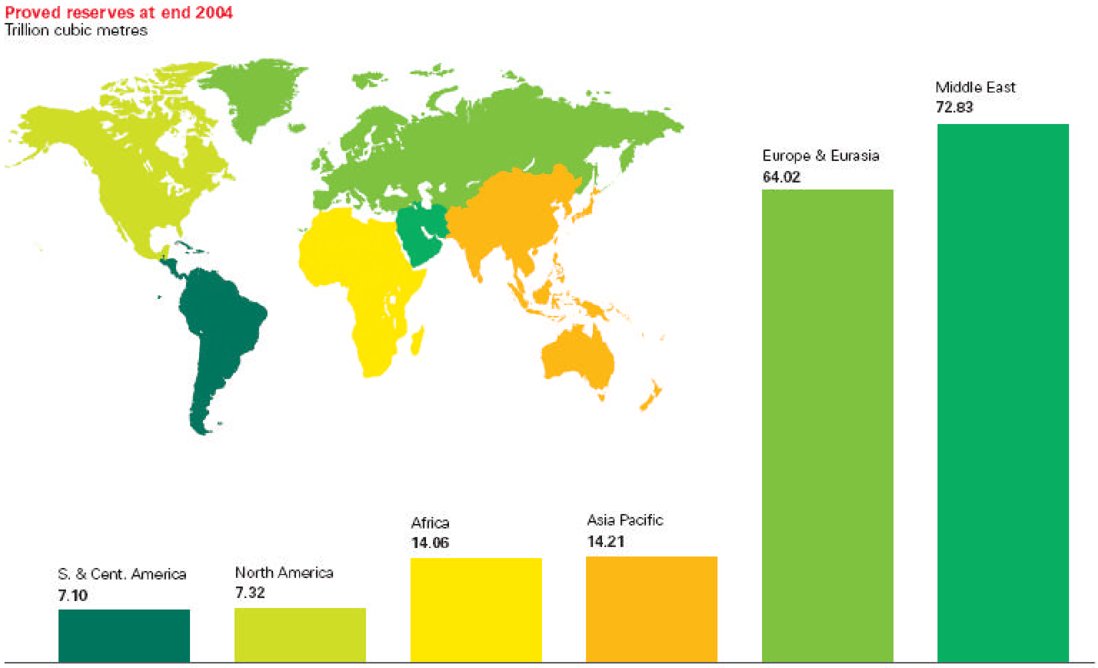

Figure 10: Proved natural gas reserves at end 2004 (BP Statistics, 2005)

The juxtaposition of dwindling oil reserves and growing militancy among many of the world's younger Muslim population could threaten economic and political stability of every nation on earth. Political leaders and policy analysts are particularly worried about the escalating conflict between the Israelis and the Palestinians and the possibility that, in the future, Islamic fundamentalists might pressure their governments to use oil as a weapon against the United States and other Western nations for supporting the Israelis (Rifkin, 2002).

During his State of the Union Address of January 31, 2006 President Bush stated that one of the "great goals" for the United States is "to replace more than 75 percent of our oil imports from the Middle East by 2025. By applying the talent and technology of America, this country can dramatically improve our environment, move beyond a petroleum-based economy, and make our dependence on Middle Eastern oil a thing of the past."

The oil era is awaiting the end of its heyday; the world is running out of cheap oil, greenhouse gases cause serious threats for our environment, and our dependence on foreign oil contribute to our geopolitical concerns. These aspects put a significant pressure on the fossil fuel vehicle regime, both external and internal. The existing regime cannot solve the problems; although fuel efficient cars, like hybrids, can have a positive impact on all three changes, they are not a solution for the long run since gasoline is still needed to fuel them. Therefore there is a need for alternative sources of energy to fuel our future economy and to solve the problems at the landscape level. Hydrogen and fuel cell vehicles have the potential to take over oil and combustion engines and are seen as very promising. Although the technology is not fully developed and cost effective yet, the 'windows of opportunity' that are created by the changes at the landscape level and the internal regime pressures have a positive impact on the developments. In the next sections I will discuss the developments of hydrogen technologies that put pressure on the existing regime from the micro level of the Multi-Level Perspective.

4.3 Hydrogen Technology

As we have seen in the previous section, landscape pressures influence hydrogen research and create opportunities for the development of hydrogen applications and production methods, which again put pressure on the existing regime. Although the existence of new technologies in actual niche markets is still very limited, as we will see in section 4.3.5, several new promising hydrogen production technologies are developed that are expected to enter niche markets sooner or later.

In this section I will first shortly explore the different hydrogen production methods and niches, there advantages and disadvantages and the expectations about the technologies. These production methods each contain a script regarding centralized or decentralized production, which, as we will see in chapter 6, is relevant for the impacts on our society. After exploring the production technologies, storage, distribution and fuel cell technologies will be discussed. In section 4.3.6 the co-evolutionary processes related to the hydrogen infrastructure will be analyzed, followed by an analysis of the influence of promises and expectations on the developments and on the existing regime in section 4.3.7. I will end this section with a summary and technological foresight of the technologies and of likely infrastructures for the future hydrogen economy.

4.3.1 Hydrogen Production

Hydrogen is not an energy source, but, like electricity, an energy carrier. Therefore it is necessary to produce hydrogen from an available primary fuel source. Today there is a wide arrange of production methods and a lot of research is going on to further develop these various methods. Figure 11 shows the most obvious pathways for the production of hydrogen from different primary energy sources (Ewan and Allen, 2005). Today the two most common pathways of producing hydrogen are reforming of natural gas (NG) and electrolysis of water using electricity.

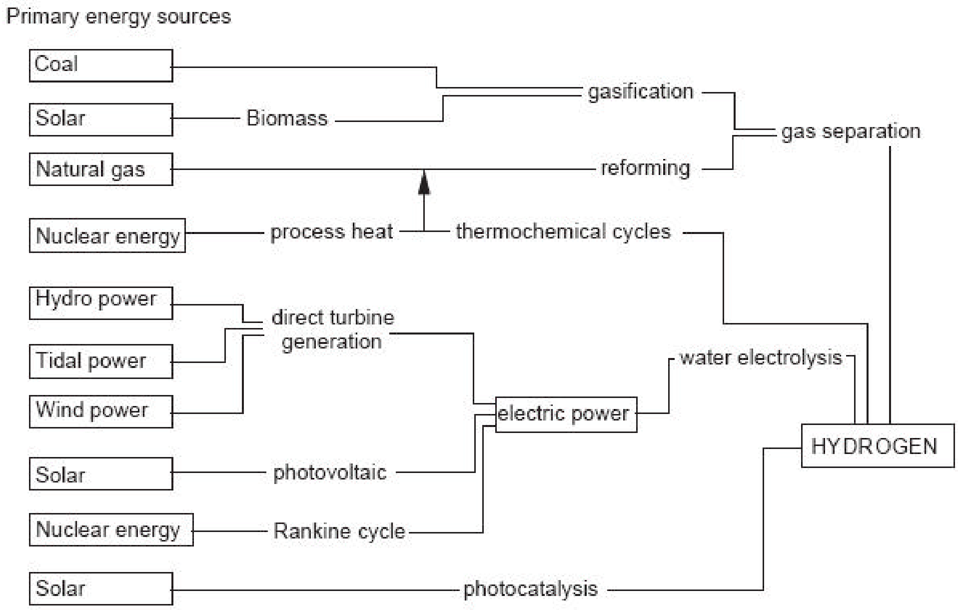

Figure 11: The primary energy sources considered and their routes to hydrogen (Ewan and Allen, 2005)

4.3.1.1 Hydrogen from Natural Gas

In the U.S. 95% of the hydrogen is produced by using natural gas. This production method is the most cost effective method available today and according to an influential report of the National Academies, the unit cost of hydrogen, based on natural gas, could be reduced from $3.51/kg to $2.33/kg (National Academies, 2004). Advantages of natural gas are the wide availability, the easiness to handle, and the, compared to other fossil fuels, high hydrogen to carbon ratio, which minimizes the formation of byproduct carbon dioxide (National Academies, 2004).

The two main disadvantages of natural gas are the size and location of the reserves. As shown in figure 10 in section 4.2.3 natural gas reserves are, like oil reserves, mainly situated in the Middle East. In the U.S. about 15% of the natural gas is imported and imports are projected to grow significantly (Klass, 2003). Today natural gas consumption is about 23 % (EIA, 2005c) of the total energy consumption in the U.S., or 23 trillion cubic feet (tcf) (EIA, 2006), but, the demand for natural gas is expected to continue to increase significantly coming decades. Not just because of population growth, but also because the fuel is the cleanest burning fossil fuel known, and up until recently, has been marketed at acceptable prices (Klass, 2003). Trends in natural gas demand indicate that shortages of natural gas and significant cost increases would be expected to occur in this decade and then begin to cause serious supply problems in the next 20-30 years (Klass, 2003). Natural gas will peak even earlier when a large fleet of FCVs needs to be fueled by hydrogen produced from natural gas. Replacing 40% of ground transportation fuels with hydrogen in 2025 would probably require an additional 10 tcf of gas, plus 10% of current power usage (Romm, 2004).

For the foreseeable future, most industry analysts are convinced that natural gas and, to a lesser extent, other fossil fuels will be the primary sources of hydrogen. According to Mark Fraase, staff member of Senator Dorgan, who is the head of the

Hydrogen Caucus, "it is not feasible to give up fossil energy sources right now." "Soon the hydrogen transition will start, based on natural gas. This is the best option for getting experience."[10] Daniel Sperling, a well-known and influential scientist when it comes to hydrogen, argues the same. "There is a lot of experience with hydrogen produced from natural gas, but not with wind or other sources. Therefore we need natural gas as a source for a transition. Moreover, from a business point of view, it is clear that there will be no transition without hydrogen based on natural gas. If hydrogen produced from wind energy was only 10 percent more expensive, it would have a chance, but if it is 50 percent more expensive nobody will invest in that."[11]

Hydrogen from natural gas is, as we will see next, expected to be much more expensive than hydrogen from coal; a factor of over 300 percent. Hydrogen from natural gas therefore seems to be not the most cost-effective path as well. The experience that has been gained with the technology and the fact that hydrogen-from-coal technologies still need to be further developed and need to prove themselves, make natural gas, however, the best or even necessary energy source for the *transition* period. Moreover, technological lock-in plays a role here, as we will see in section 4.3.3. Since the demand for hydrogen will be relatively low during the first stages, the impact on the natural gas reserves is expected to be negligible. "For the next decade the use of natural gas for hydrogen will be a really small percentage compared to the amount of natural gas that is used for electricity generation", says Patrick Serfass, Director of Program and Technology Development.[12] Carbon dioxide emission will still occur when natural gas is used, but this is seen as a necessary consequence, since clean technologies are not ready yet today.

4.3.1.2 Hydrogen from Coal

Making hydrogen from coal is closely linked to making electric power from coal. This is particularly the case for gasification, a clean coal technology which will be required for making hydrogen and which also offers the best opportunity for making low cost, high-efficiency, and low emission power production through the integrated gasification combined cycle (IGCC) process. The lowest cost hydrogen coal plants are likely to be ones that co-produce power and hydrogen (National Academies, 2004).

Hydrogen from coal is seen as a very promising technology. Commercial technologies for converting coal to hydrogen are available from several licensors, the cost of hydrogen from coal is among the lowest available, and technology improvements are identified to reach the future DOE cost targets ($2.00 - $3.00 per gasoline gallon equivalent (DOE, 2005)). It is expected that hydrogen production costs with this method can be reduced to $0.77/kg (National Academies, 2004). Moreover, the U.S. has large coal reserves and is therefore not dependent on other countries. According to the National Academies' report, the United States has enough coal to make all of the hydrogen that the economy will need for more than 200 years. According to Weisz (2004), however, population and economic growth alone reduce the calculated lifetime of the U.S. coal reserves to some 90-120 years. The use of coal for conversion to other fuels would quickly reduce this lifetime even further to less than 75 years (Weisz, 2004).

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[10] Data from interview with Mark Fraaze, Staff member Senator Dorgan, North Dakota
[11] Data from interview with Daniel Sperling, University of California, Davis
[12] Data from interview with Patrick Serfass, NHA

The main problem related to hydrogen from coal is carbon dioxide emissions. The emissions from making hydrogen from coal are larger than those from any other way of making hydrogen (National Academies, 2004). To solve this problem, the possibilities for carbon capture and storage (CCS) are researched and new techniques are developed. The future of the CCS process is very uncertain. Although many scientists and industrialists consider this technology as very promising, there are still many barriers that need to be overcome. The main concern of opponents of the technology is the uncertainty of what happens with the carbon dioxide that is stored underground in deep aquifers or other geological formations, or in deep oceans. Will it stay there forever, or is it possible that slowly the carbon dioxide is released to the atmosphere again. This would cause serious problems and would undermine the function of CCS and our efforts to develop solutions for our environmental problems. Moreover, with possible future carbon taxes, the price of hydrogen from coal will increase significantly.

Despite these problems with CCS technologies, hydrogen from coal is expected to play an important role in the hydrogen economy. In his testimony to the U.S. Senate Subcommittee on Energy, Jeremy Bentham, CEO of Shell Hydrogen, stated that "[Shell Hydrogen] anticipates that the bulk of hydrogen will initially be produced, as now, from natural gas, with increasing use of coal over the course of time" (Bentham, 2005).

4.3.1.3 Hydrogen from Nuclear Energy

Nuclear energy is seen as a long-term energy resource that can serve the United States and the world for centuries. With major uranium supplies in the United States, Canada, and Australia, increased reliance on nuclear fuel supplies adds to U.S. energy security. Nuclear power reactors do not involve any carbon dioxide emissions to the atmosphere, nor do they emit any toxic air pollutants such as are committed by fossil-fueled power plants. Hydrogen can be produced using reactors for water splitting by electrolysis or by thermochemical processes (National Academies, 2004).

Renewed interest in nuclear power is rising. The expectations are that the role of nuclear energy in the energy supply will increase again and new developments are considered to be promising. The United States decided in the 1970s against commercial reprocessing, primarily out of concern that separated plutonium might be diverted by terrorists or used by governments elsewhere to inaugurate nuclear weapons programs. Further, with uranium in ample supply it was less expensive to dispose directly of the spent fuel. However, Congress in November 2005 moved to appropriate funds for the development of technologies to recycle existing spent fuel – an initiative that, if pursued, may lead to major changes in the U.S. waste disposal program and revive proliferation concerns (Bodansky, 2005). In 2002, the so-called "Generation IV technologies" reactor concepts were selected. These promising technologies are being further explored for availability beyond 2025. The goals for the proposed advanced reactor systems are to improve the economics, safety, waste characteristics, and security of the reactors and the fuel cycle (National Academies, 2004). Those are the main disadvantages of nuclear energy and nuclear developments will be encumbered by their lack of public acceptance.

The nuclear industry is convinced that nuclear energy will play a role in a future hydrogen economy and they are putting a lot of effort in the development of new technologies. At the annual meeting of the World Nuclear Association in London September 2002, the group's director general, John Ritch, touted what he called the "hydrogen-nuclear economy." He envisions "an entirely clean energy global economy, with nuclear power supplying not only electricity and clean water, but also energizing transport of all kinds" (Motavalli, 2003). Kenneth Schultz, Director of Operations of General Atomics, is also convinced that there will be absolutely a role for nuclear energy in the hydrogen economy. "If not, then there will be no hydrogen economy." Like many others, he expects, however, that there will be a mix of energy sources for hydrogen production. According to Schultz the changing vision in U.S. politics with regard to nuclear energy is caused by an increasing awareness of the problems that are related to the alternatives. In the past nuclear energy was feared and at the same time natural gas was cheap, much cheaper than nuclear energy. This is changing, however. Moreover, renewables are still too expensive.[13]

Regarding to the carbon dioxide problem that comes with hydrogen form coal, Kenneth Schultz, together with other scientists and engineers at General Atomics, has been working on a solution that deals with this problem and at the same time favors the nuclear industry. They have developed a technology that improves the coal gasification process and that can even produce synfuels from carbon dioxide, by using (nuclear) hydrogen. As long as the hydrogen demand in the transportation sector is still low, hydrogen can be used to produce these synfuels, which can be transported through existing oil and natural gas pipelines and which can be used as a fuel in conventional internal combustion engine vehicles. According to Schultz, this approach is cost-effective with a $30/ton CO_2 credit *[to compare: CO_2 permit prices in Europe have collapsed recently and on May 31, 2006, permits for December 2006 were $21/ton]*. General Atomics is planning to start, together with the government, a pilot project in order to further explore the possibilities of this promising technology.[14]

4.3.1.4 Hydrogen from Electrolysis

Electrolysis of water, the process to disassociate water into its separate hydrogen and oxygen constituents, has been in use for decades, primarily to meet industrial chemical needs. Unlike the other production methods described in this chapter, electrolysis is, of course, not an energy source. Electrolysis will therefore always be used in combination with an energy source, e.g. renewable energy or grid electricity. As will be discussed later, for the far future, the main part of the hydrogen is expected to come from renewables. If this happens, electrolysis will probably play a key role in hydrogen production. For a transition period electrolysis is an interesting technology as well. Therefore it is important to briefly discuss this technology as well.

While more expensive than steam reforming of natural gas – hydrogen from electrolysis, using grid electricity, is estimated to cost $4.00/kg for the 2010-2030 timeframe (National Academies, 2004) – electrolysis is seen as an important process in the transition to a hydrogen economy, since it can be applied easily and basically everywhere where grid electricity is present.

Significant improvements are needed though. According to Romm (2004b) replacing one-half of U.S. ground transportation fuels in 2025 with hydrogen from electrolysis, using existing technologies, would require about as much electricity as is sold in the U.S. today. Moreover, prices are in the range of $10 per kg today (Romm,

[13] Data from interview with Kenneth Schultz, General Atomics
[14] Ibid

2004b), which is still not close to the DOE's goal of $2.50/kg (based on decentralized production) by 2010 (National Academies, 2004). Technological improvements are therefore needed to make electrolysis – and therefore also some forms of renewable hydrogen – more competitive. The expectations are that this can be made possible in the near term and electrolysis is expected to play a major role in the hydrogen economy, especially for the transition period, by either using electricity from the grid or renewable energy, and for the long term when renewable technologies are becoming more mature and cost effective, as discussed below.

4.3.1.5 Hydrogen from Wind Energy

Of all renewable energy sources, using wind energy for hydrogen production, by means of electrolysis, is the most mature and cost effective technology. In the near to medium term, wind energy is seen as having the greatest potential for producing pollution-free hydrogen.

Compared to the previous discussed production methods, there are several advantages to hydrogen produced from wind energy (and more or less to renewables in general). The main advantage is that wind energy is a clean energy source. There is no emission of carbon dioxide and other greenhouse gases and pollutants. In addition to that, wind energy is infinite, so the world will never run out of wind. Finally, wind energy is a domestic energy source, which increases our energy security. Thus, wind energy has the potential to cater to all landscape and regime pressures that are discussed in section 4.2.

There are, however, also some drawbacks related to wind energy. First of all, siting issues can cause problems. Windmills take up space, and more importantly, have an impact on the landscape. Second, there are environmental issues that need attention, for example the impact on birds in an area. Third, although the technology is becoming more and more mature, there are still several technical problems that must be dealt with, like efficiency and vibrations. Finally, wind energy's most serious drawback is its intermittence, both in time and space, and mismatch with demand (Smil, 2003); peak wind flows only rarely coincide with the time of the highest demand. Inevitably, these realities complicate efficient commercial utilization. Many densely populated areas with high electricity demand experience long seasonal periods of calm or low wind speeds and hence are utterly unsuitable, or only marginally suited, for harnessing winds energy. In contrast, most of the best sites are far from major load centers in thinly populated or uninhabited regions (Smil, 2003). Hydrogen production can, however, be an excellent solution for that. When electricity demand is low, the wind energy can be used to produce hydrogen. When demand is high, this hydrogen can then be used to generate electricity. Thus, apart from producing hydrogen for transportation purposes, hydrogen-from-wind can be a great solution for the most serious drawback wind energy faces today.

Wind energy is one of the most cost competitive renewable energy technologies available today and has been lauded as one of the fastest-growing energy sources. Wind driven electricity generation is far ahead of other solar based techniques both in terms of operational reliability and unit costs (Smil, 2003). At the best wind sites, even unsubsidized wind electricity is already below 4 cents per kilowatt-hour (kWh) and is competitive with fossil fuel generation (Turner, 2004). These costs are expected to drop even more as the technology improves further and the market grows. According to Randall Swisher, Executive Director of the American Wind Energy Association

(AWEA)[15], "[...] the wind industry is looking forward to several record-breaking years in a row. Companies can now plan for growth, create jobs, and provide more clean power to customers nationwide. We are finally beginning to tap into wind energy's enormous potential" (AWEA, 2006).

The National Academies' report estimates that using today's technologies, hydrogen can be produced at good wind sites for approximately $6.64/kg. As stated in section 4.3.1.4 hydrogen from electrolysis is estimated to cost $4.00/kg for the 2010-2030 timeframe and with wind electricity already competitive with fossil fuel generation, hydrogen-from-wind can thus reach this price level as well. With future estimated improvements in the technology, hydrogen produced from wind without grid backup is estimated to cost $2.86/kg, while for a system with grid backup it is $3.38/kg (all without financial incentives). The report states, however, that wind-electrolysis-hydrogen production systems are currently far from optimized and still face many barriers to deployment and therefore deserve more focused attention in the DOE's hydrogen program.

Despite the fact that hydrogen from wind is the most mature and cost effective technology among renewables, and is seen as having the greatest potential for producing pollution-free hydrogen for the near and medium term, hydrogen from wind is not expected to play a major role earlier than the long term. Compared to, for example, natural gas, the technology is much more expensive, and as Daniel Sperling stated, as mentioned before, "If hydrogen produced from wind energy was only 10 percent more expensive, it would have a chance, but if it is say 50 percent more expensive nobody will invest in that."[16] According to Kirk Martin, working on offshore wind farms for Georgia Institute of Technology and Georgia Power, a Southern Company, the intermittence of wind energy is one of the main problems that prevent companies from investing in it. "Utilities are hesitating to invest in wind farms because the benefits and returns are not known on forehand. It is possible that you invest in it and that the first few years the wind is much less than expected. This makes business decisions more difficult".[17] For these reason it is unlikely that hydrogen from wind will gain a significant market share in the near term. It can, however, play a role in remote areas or in areas where a natural gas infrastructure is absent.

4.3.1.6 Hydrogen from Biomass

Although the use of biomass (fuel wood, charcoal, crop residues, etc.) as a fuel has increased over the last couple of years, mainly in the form of ethanol, there are some serious drawbacks and practical limits. The National Academies' report estimates that if the U.S. vehicles were to run solely on hydrogen, the amount of biomass needed to satisfy 100 percent of the hydrogen demand would require roughly 282.000 square miles for bioenergy crop farming. This comprises an area of land that is approximately 40% of cropland currently used for crops in the United States. In addition to that, the intensified use of cropland used for biomass energy would carry all the well-known requirements –

[15] AWEA is a national trade association that represents wind power plant developers, wind turbine manufacturers, utilities, consultants, insurers, financiers, researchers, and others involved in the wind industry (http://www.awea.org)

[16] Data from interview with Daniel Sperling, University of California, Davis

[17] Data from interview with Kirk Martin, Georgia Institute of Technology

like large-scale use of machinery, high amounts of inorganic fertilizers, pesticides and herbicides – and environmental impacts – like excessive soil erosion, complexion of soils, and nitrogen and phosphorous leaking into waters – encountered in highly productive agriculture (Smil, 2003). Finally, hydrogen production from biomass is an inefficient and expensive process price of currently about $7.05/kg by gasification in a mid-size plant. The committee estimates the possible future technology price for hydrogen from gasification of biomass to be $3.60/kg, which is noncompetitive relative to other hydrogen production technologies (National Academies, 2004). It seems therefore very unlikely that hydrogen from biomass will play an important role in the hydrogen economy. Since this technology seems not to be very promising, not a lot attention is paid to developments and hydrogen from biomass is not expected to play a main role in the future.

4.3.1.7 Hydrogen from Solar Energy

It has been estimated that solar energy has the potential to meet global energy demand well into the future. Like wind, solar energy has many advantages above other energy sources (clean, infinite, domestic) and has the potential to deal with the three changes at the landscape level. Moreover, solar cells have less impact on the environment than wind turbines. Like wind energy, however, there are still technical problems that must be dealt with. In fact, solar energy is less mature than wind energy, and the technological performances still form a serious drawback for solar energy. There are, however, many promising technologies and a lot of effort is put into further development and improvement of the technology. Finally, like wind energy, the intermittence and mismatch with demand of solar energy is, to a lesser extent, another drawback. Here again, hydrogen can be a solution.

Despite these drawbacks, recent years have shown a promising growth in the solar photovoltaic sector; building of solar cells increased by 60% between 2003 and 2004. The annual growth rate was running at a 43% year on year increase before 2004. Capacity for Solar PV energy generation was up almost 35% each year during the same period (ABS, 2006). According to the ABS it is, however, difficult to predict further developments. The last two years have seen silicon shortages and with competition for the raw material has come competition and higher prices for companies wanting to engage in solar development (ABS, 2006). New technologies are therefore developed. Emerging thin film cell manufacturing holds much promise because the coatings use less silicon than traditional films and can be manufactured at low cost and in large volume (ABS, 2006). To demonstrate this technology, by 2002 BP had installed translucent awnings embedded with thin-film photovoltaics at 250 of its gas stations around the world, keeping customers dry while powering the pumps. “It becomes a window pane, or it could be a shading application, or it could be a skylight application. We are doing all of those,” says BP's Arya (Fairley, 2002). Despite such promises, however, it could take decades with thin films to transform solar power from a marginalized technology to a mainstream source of energy (Fairley, 2002).

When it comes to hydrogen production costs, there is still a long way to go for solar energy. In the National Academies’ report the production costs of hydrogen by using electricity from current solar photovoltaic (PV) cells (today the most common technology) were estimated to be $28.19/kg. The expectations are that this price will drop to \$6.18/kg (National Academies, 2004). This is still much higher than the other production methods and some serious technology breakthroughs are needed in order to make solar-hydrogen cost effective and competitive.

Scientists and engineers at companies, research institutes and universities are trying to improve current technologies and develop new ones. Research is being done to create aqueous photo electrochemical cells for direct conversion of solar energy to hydrogen. In this method, light is converted to electrical and chemical energy. A solid inorganic oxide electrode is used to absorb photons and provide oxygen and electrons. The electrons flow through an external circuit to the metal electrode, and hydrogen is liberated at this electrode. If successful, such a method holds the promise of directly providing low-cost hydrogen from solar energy. However, this method also has to deal with a major cost challenge (National Academies, 2004). One of the promising Direct Solar Electrolysis technologies is the Tandem Cell™, developed by Hydrogen Solar Ltd[18]. Studies show that an array of cells covering a standard Southern Californian double garage will fuel a hydrogen vehicle for 11.000 miles of driving per year without visiting a filling station. The only input to this system is sunlight and water, and there are zero carbon emissions resulting from the complete energy chain. With an efficiency of 8 percent already, the efficiency of the Tandem Cell™ is on target for reaching the 10 percent level for commercial viability (Hydrogen Solar, 2005). According to Ron Larson, chair of the American Solar Energy Society (ASES), two other promising technologies are the spectrum splitting approach and the Zinc oxide approach.[19] Both approaches make use of concentrator photovoltaic (CPV) which is shown in figure 12. The function of the dish is to increase the electrical output of the PV panel significantly. The spectrum splitting approach combines heat energy (infrared) with the electricity to separate water into hydrogen and oxygen. Harnessing the thermal portion of the solar spectrum offers a potential for higher efficiency and increased hydrogen production capability. With today's solar cell technologies, it is therefore possible to achieve a 50% conversion efficiency of the solar energy to hydrogen through high temperature electrolysis. It is expected that hydrogen production through thermal-CPV electrolysis has the potential to be equally as attractive, if not more so, as 'wind hydrogen' (Thompson et al, 2005). The Zinc oxide approach also makes use of concentrated solar radiation, but instead of splitting the solar

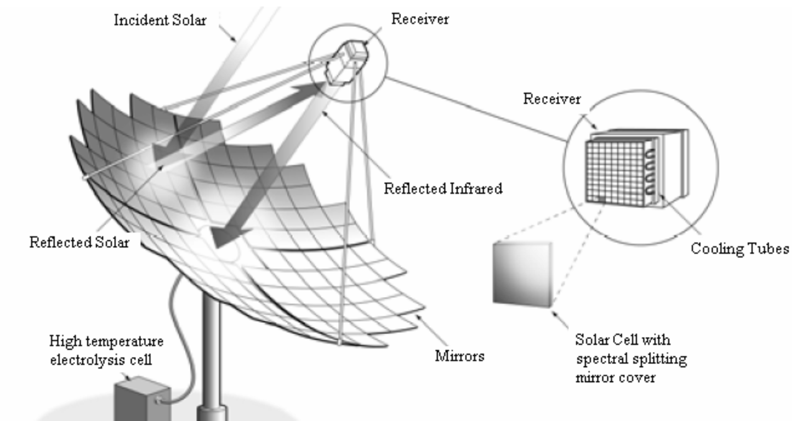

Figure 12: Solar generation of Hydrogen using CPV (Thompson et al, 2005)

[18] http://www.hydrogensolar.com/index.html
[19] Data from interview with Ron Larson, ASES

spectrum, the energy is used to split ZnO in its elements Zn and O. The Zinc then reacts with water to produce ZnO and hydrogen. The ZnO will be split again and so the process continues (Steinfeld, 2003):

$$ZnO \; ? \; Zn \; ? \; \frac{1}{2}O$$

$$Zn \; ? \; H_2O \; ? \; ZnO \; ? \; H_2$$

This approach is expected to become cost effective as well.

As stated before, solar energy has the potential to meet global energy demand well into the future. According to Jeremy Bentham of Shell Hydrogen, none of the challenges related to hydrogen from solar are unsolvable (Bentham, 2005). Although hydrogen-solar technologies still face many problems and are, by far, not cost effective yet, hydrogen from solar is, together with hydrogen from wind, seen as having high potential for the future and is expected to play a major role in a hydrogen economy, but only in the very long run. According to Debbi Smith from the NHA "renewable hydrogen is eventually the goal. For some countries where a lot of renewable energy sources are available, like Iceland, it might make sense to go straight to renewables, but not for the U.S. We believe that in a transition, fossil fuels need to play a role. You cannot simply turn off a trillion dollars infrastructure and turn on a new one, but when natural gas prices will rise, other options will be cheaper, so then you can pursue those options."[20]

4.3.1.8 (De)centralized Scripts

Every production method contains a certain 'script' related to the supposed infrastructure; the internal characteristics of the technology presuppose a certain infrastructure. Three general strategies for the hydrogen fuel infrastructure are distinguished (MacLean and Lave, 2003). The first is production at large centralized facilities and then distribution via pipelines or trucks to refueling stations. This way of production and distribution already serves the needs of today's industrial demand. Hydrogen has been handled and sent through hundreds of miles of pipelines with relative safety for the oil, chemical, and iron industries. I will call this production strategy 'macro-production'. Second is the option of producing hydrogen at a large number of decentralized facilities, such as service stations, where it would be delivered to vehicles. The energy station of the future might produce hydrogen on demand from natural gas, other compounds or even water. This form of decentralized hydrogen production will be referred to as 'meso-production'. The ultimate solution might be solar powered hydrogen filling stations, where electricity generated by the sun (or by a windmill) is used to extract hydrogen from water[21]. This is not as far out as it sounds. Two such stations already are operating in Southern California. Finally, the hydrogen could be produced by reforming a hydrocarbon fuel (e.g. gasoline, methanol, natural gas) onboard a vehicle (MacLean and Lave, 2003). This last production strategy is not of interest for my research, since a new infrastructure is not necessary for this option. However, by splitting decentralized production in two forms, I will distinguish a fourth strategy, 'micro-production'. Like meso-production, micro-production is a

[20] Data from interview with Debbi Smith, NHA
[21] http://www.fuelcells.org/hydrogen/basics.html

decentralized production path. However, production does not happen at service station, but at people's homes. I will now briefly look at what production methods contain what script.

- The reforming of natural gas to hydrogen process has a script that suits both centralized and decentralized production methods; it does not require large complex installations and an extensive natural gas infrastructure already exists in the U.S. even to homes, so natural gas can be distributed easily. At least for the near term meso-production based on natural gas is considered to be the best solution.
- The coal to hydrogen script is a completely macro-production script, for several reasons. First of all, the gasification process is a complex process and requires high-tech technology. Economies of scale are highly favorable in this situation. Moreover, since co-production of hydrogen and power is seen as the best solution, integration with a power plant is most desirable. Second, a substantial coal infrastructure already exists, leading to centralized power plants. Third, carbon dioxide sequestration and storage is required to create clean hydrogen. These complex techniques are not suitable for distributed hydrogen production and thus, are centralized plants the best option. Although decentralized natural gas reformers also emit carbon dioxide, the problem is not as urgent, since natural gas is much cleaner than coal.

Obviously centralized plants produce large amounts of hydrogen compared to decentralized facilities. Macro-production methods like coal are therefore only a viable option for making hydrogen when the demand for hydrogen becomes large enough to support an associated very large distribution system. This aspect of the script is of importance for the transition period, when demand is still small. Coal, and centralized plants in general, will not be cost effective during these periods.

- Like coal-fired plants, nuclear energy is found today in a centralized form, and probably will be in the future. Again the complexity of the technology and installations make the nuclear industry unsuitable for small scale levels. Although there is no emission of carbon dioxide, and thus no sequestration needed, the character of the technology, the problems with safety, waste and security, require trained specialists and special facilities. It is very unlikely that technological developments will change this situation and that nuclear meso-production facilities will be built; the nuclear-hydrogen script is a centralized script, and thus only useful when the hydrogen demand is large enough.
- Electrolysis contains a script that is well suited with the meso- and micro-production methods; small facilities can be built at existing service stations or at homes. It can, however, also serve a centralized hydrogen plant. In addition, electrolysis' script is well matched to renewable technologies.
- Wind energy contains both a centralized and decentralized script. It is possible that a windmill next to a service station generates the electricity needed for the hydrogen production. There is, however, an important limit. Windmills need a lot of space and can therefore not serve meso-production for densely populated areas, where the hydrogen demand is the highest. Along highways and in remote areas, windmills can however play an important role for meso-production. The same applies for micro-production. Moreover, the relatively high costs of a windmill make this production method unlikely for micro-production at all. For densely populated areas, apart form other energy sources, nearby giant wind farms that produce, store, and distribute hydrogen could satisfy the demand.

- Biomass hydrogen is most suitable for centralized production methods. It is not practical and probably not efficient and cost effective, to transport the biomass to service stations and homes in order to produce hydrogen on-site. Moreover, it is unlikely that a homeowner, for example, can and will grow enough biomass to fuel her or his own car.
- Producing hydrogen by using solar energy is the ultimate solution for decentralized hydrogen production, both meso-production as micro-production. If the performance and efficiency of solar cells increase, solar cells can be placed on top of the roofs of service stations and homes as shown in figure 13. With new technologies, solar cells can even be integrated in windows. Therefore, solar cells are, when cost effective, the ultimate decentralized solution.

Figure 13: Micro-production of solar hydrogen (Hydrogen Solar, 2006)

According to Romm (2004b), centralized production of hydrogen is the ultimate goal. He states that a pure hydrogen economy requires that hydrogen will be generated from CO2 free sources, which would almost certainly requires centralized hydrogen production closer to giant wind farms or at coal/biomass gasification power plants in which CO2 is extracted for permanent underground storage. That will require some way of delivering massive quantities of hydrogen to tens of thousands of local fueling stations. Maria Curry-Nkansah from BP agrees with that. "In the first stages of the transition hydrogen will be mainly produced on site. Later on, when demand grows centralized production will be the best option and pipelines are likely to be used for transportation."[22]

Patrick Serfass from the NHA states that one of the advantages of hydrogen is that both centralized and decentralized production is possible. You do not necessarily have to distribute the hydrogen, which makes it a very flexible fuel. Because of economies of scale centralized production is favorable if the demand is high. Hydrogen can then be produced at lower costs. But for remote areas or for places where the demand is low, decentralized production methods can be applied. A mix of centralized and decentralized production is therefore Serfass' expectation.[23]

[22] Data from interview with Maria Curry-Nkansah, BP
[23] Data from interview with Patrick Serfass, NHA

Centralized and decentralized systems influence our society in a different way. This can be a reason to favor a certain production method. In chapter 6 I will further analyze these aspects.

Centralized production methods, obviously require extensive distribution systems from the plants to the fueling stations. In section 4.3.3 I will further explore those distribution systems, but before I do that, I will first discuss another element of the hydrogen technology: hydrogen storage.

4.3.2 Hydrogen Storage

Although hydrogen has a much higher energy content by mass than any other fuel, the energy content by volume is significantly lower, about 70% lower than natural gas. This causes serious problems related to hydrogen storage. Running a fuel cell car on pure hydrogen, the option now being pursued by most automakers and fuel cell companies, means the car must be able to safely, compactly, and cost effectively store hydrogen onboard. This is a major technical challenge (Romm, 2004b). The most mature storage options are liquefied hydrogen and compressed hydrogen gas. Storing enough hydrogen to power a car requires, however, a large tank. At room temperature and pressure, hydrogen takes up some 3000 times more space than gasoline containing an equivalent amount of energy (Romm, 2004b). As illustration: with the technology of the late nineties, the compressed hydrogen tank size required to contain 6.8 kg hydrogen for a 1500 kg vehicle with a driving range of 560 km is 340 liter at 25 MPa. A typical gasoline tank for such a vehicle is 70 liter (Svoboda et al, 1997).

Liquid hydrogen is widely used today for storing and transporting hydrogen. Indeed, for storage and fueling, liquids enjoy considerable advantages over gases: they have high energy density, are easier to transport, and are typically easier to handle. Hydrogen, however, is not typical. It becomes a liquid only at –253°C, just a few degrees above absolute zero. It can be stored only in a superinsulated cryogenic tank (Romm, 2004b).

Current energy storage technologies are insufficient to gain market acceptance. Thus, the challenge for auto engineers who want to match today's 300-mile vehicle range is to discover a way to store enough compressed hydrogen in the vehicle without consuming too much space. Much of the technology that automobile companies are now using in their prototypes involve, despite their problems, compressed hydrogen tanks, liquid hydrogen tanks, or getting the hydrogen from another source, namely methanol or gasoline. This is the indirect way of using hydrogen for fuel cell cars. Researchers are, however, also examining an impressive array of hydrogen storage options, so that elemental hydrogen may be stored by itself. Metal hydrides and chemical hydrides are therefore being developed and may become viable in the future. Work is also being done to combat the hydrogen storage problem indirectly with the usage of acidic electrolytes to increase the temperature at which the cells run at, and increasing the productivity of the hydrogen stored. This would mean less would need to be stored. One of the methods of direct storage that appear to be the very promising these days is the use of carbon nanotubes. In 1996 Terry Baker and Nelly Rodriguez from Northeastern University, claimed to have created a carbon nanotube that can store enough hydrogen gas to power a car for 5,000 miles, with a 25 liter tank (Svoboda et al, 1997; Babson, 1997).[24] In their experiment the carbon nanotubes were capable of storing 75% of their own weight. These results, however, have been received with a lot of skepticism, because other researchers could, by far, not reach this large storage capacity and because Terry Baker and Nelly Rodriguez kept the process secret for commercial reasons. Despite the skepticism, their remarkable claims have lit a fire under their rivals. The technology is seen as promising and has attracted considerable interest recently due to several reports of high hydrogen storage capacities at room temperatures, a main advantage. Today the storage results on nanocarbons vary widely, from 0-60 wt% (NREL, 2002). Work at NREL indicates that a maximum capacity for adsorption of hydrogen on so called single-wall nanotubes is ~8 wt% (NREL, 2002). The DOE 2015 hydrogen storage system target is 9wt%, in order to make fuel-cell cars practical and commercial attractive (NREL, 2006). Although the developments look promising, the technology is still far from being commercialized. Much more research is needed to explore the qualities of the different materials, their behavior over time (the nanotubes tend to lose capacity), to find the best materials, to fight the costs, etc. Thus, more technological breakthroughs are needed to make nanotubes an attractive means of storage. Utgikar and Thiesen (2005) state that storage as a liquid or compressed gas have, however, advantages over these other methods as these two involve physical storage of free hydrogen, which can be easily supplied to the engine without any need for complex systems. Systems of greater complexity are required to obtain hydrogen if it is stored by using metal or chemical hydrides. Car manufacturers prefer these less complex systems and appear not to put a lot of effort in the development of hydrides-storage-systems and nanotubes.

Storage is seen as one of the main problems related to a hydrogen transition. This especially relates to onboard storage of hydrogen. Today's storage systems take up a lot of space; space that is at the cost of the available space in the trunk. Moreover, safety plays an important role in especially onboard storage. However, according to Rick Zalesky, Vice President Hydrogen Business of Chevron Technology Ventures, storage problems do not only relate to onboard storage, but also to storage at production sites. "If hydrogen is stored as a compressed gas, you need a lot of space. Storing it as a liquid is expensive and not energy wise."[25] According to Romm (2004b) some 40 percent of the energy of the hydrogen is required to liquefy it for storage. Liquefying one kilogram of hydrogen using electricity from the U.S. grid would by itself release some 18 to 21 pounds of carbon dioxide into the atmosphere, roughly equal to the carbon dioxide emitted by burning one gallon of gasoline. These are the biggest problems today and technological breakthroughs are needed according to Zalesky.[26]

Apparently the storage problems relate to the centralized and decentralized scripts as well; since storage as a gas is expected to be the method that will be applied mostly, centralized hydrogen plants need a lot of space for storage, while this problem is partially eliminated when hydrogen is produced at meso- and micro-production facilities, especially on demand. This seems to be more desirable, although, apart from

[24] In their research 30 liter hydrogen was stored in one gram of carbon. The 25 liter tank will weigh 87 kilogram.
[25] Data from interview with Rick Zalesky, Chevron/Texaco
[26] Ibid

Chevron/Texaco, most developers seem not to bother about his problem and consider centralized production as the future production method.

4.3.3 Hydrogen Distribution

As we have seen in the previous sections, centralized hydrogen production methods are expected to play a major role in the hydrogen future. Obviously this requires extensive distribution systems from the plants to the fueling stations. Moreover, the design of an infrastructure, including gas pipelines and rail lines for delivering inputs for producing hydrogen, will be a very important integral part of the system. The challenges in achieving the best delivery system are to match the resources for hydrogen inputs and the delivery system, to select the site for hydrogen production, and to establish a viable transportation network (Tseng et al, 2005).

Hydrogen distribution either occurs by using pressurized cylinders or tank containers in combination with trucks and trains, or by using pipelines. It is usually delivered as a compressed gas or else as a liquid (IFP, 2004). For both transportation through cylinders as for pipelines, however, it implies that the transportation costs of hydrogen are much higher than those of other fuels, since hydrogen has a very low energy value by volume. Delivering hydrogen from large plants to dispersed small hydrogen users is now roughly five times more expensive than producing the hydrogen (Sperling and Ogden, 2004). Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100-200 miles from the production facility. For longer distances of up to 1,000 miles, hydrogen is usually transported as a liquid in superinsulated, cryogenic, over-the-road tankers, railcars, or barges, and then vaporized for use at the customer site (Turner et al, 2004; DOE, 2006).

The most commonly used system of hydrogen transmission these days is the pipeline, with the world network totaling over 2,500 km. Most pipe systems are located in Europe (1,500 km) and the United States (900 km). The operating entities of these pipelines are mainly large industrial gas producers such as Air Liquide, APCI, etc. (IFP, 2004; Suzuki et al, 2005), or organizations such as NASA who use large amounts of hydrogen for specific purposes (Suzuki et al, 2005). Many experts expect that pipelines will be the main mean of transportation of hydrogen in the future.

The design of hydrogen infrastructure and systems must account for existing infrastructure for moving natural gas, coal, biomass, water, and possibly other renewable energy sources. The fact that transporting these resources is much cheaper than constructing hydrogen pipelines affects the optimal design of the hydrogen production and delivery system (Tseng et al, 2005).

Existing infrastructures could, however, provide a basis for developing a hydrogen supply system. Excess capacity in the current industrial hydrogen infrastructure might be used to provide hydrogen to early vehicle projects. Today’s gasoline stations are well located to serve customers and might become sites of future hydrogen stations. Future hydrogen pipelines might be built along existing rights of way for gas pipelines, electric transmission lines, major highways, or railroads (Ogden, 2004). It has been suggested that the existing natural gas pipeline system might be used to carry hydrogen. As a near term strategy, hydrogen could be blended with natural gas at up to 15 to 20 percent hydrogen by volume without changing the gas pipeline distribution system. For higher fractions of hydrogen or pure hydrogen, the parts of the natural gas distribution system, such as seals and meters, and end-use systems, including engines or burners, would require changes.

Existing primary resource extraction and delivery systems for natural gas and coal are well established to connect resources to conversion sites (Ogden, 2004). Natural gas in the U.S., which supplies 23% of all of the energy used, is delivered to customers through a safe, sound, 2.2-million miles underground pipeline system that includes 1.9 million miles of local utility distribution pipes (1.1 million miles of utility mains, plus 800,000 miles of utility service lines) and 300,000 miles of transmission lines (AGA, 2005). In figure 14 the major natural gas pipeline routes in the U.S. are shown. Figure 15 shows how the hydrogen and natural gas pipeline is networked in the U.S. by integrating the natural gas pipeline system in figure 7.

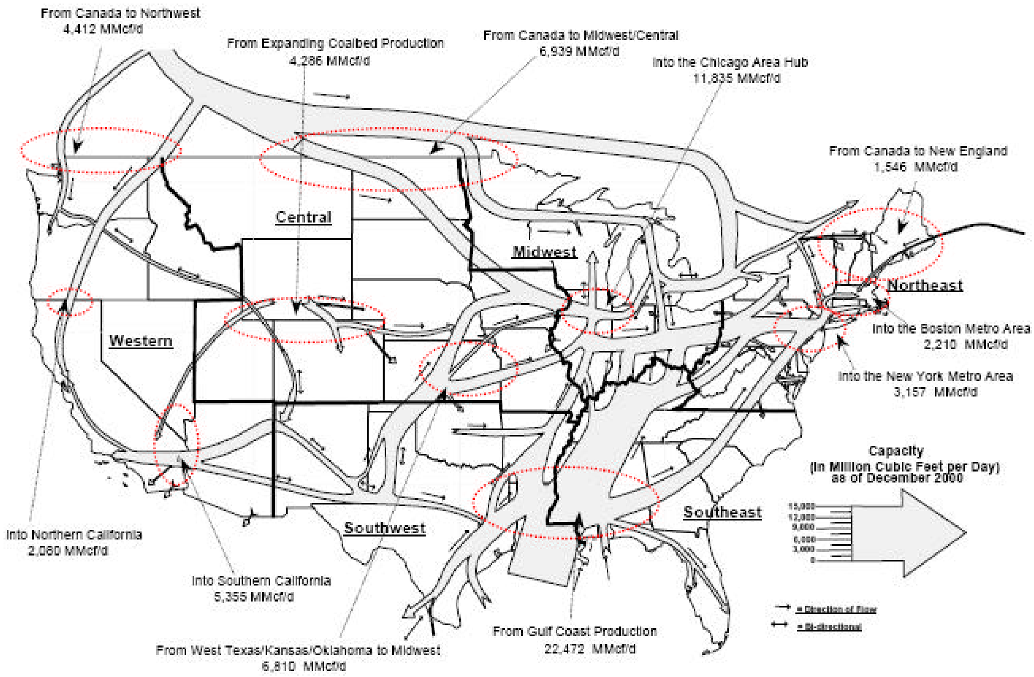

Figure 14: Major Natural Gas Pipeline Transportation Routes and Capacity Levels at Selected Key Locations, 2000 (Source: EIA, 2001)

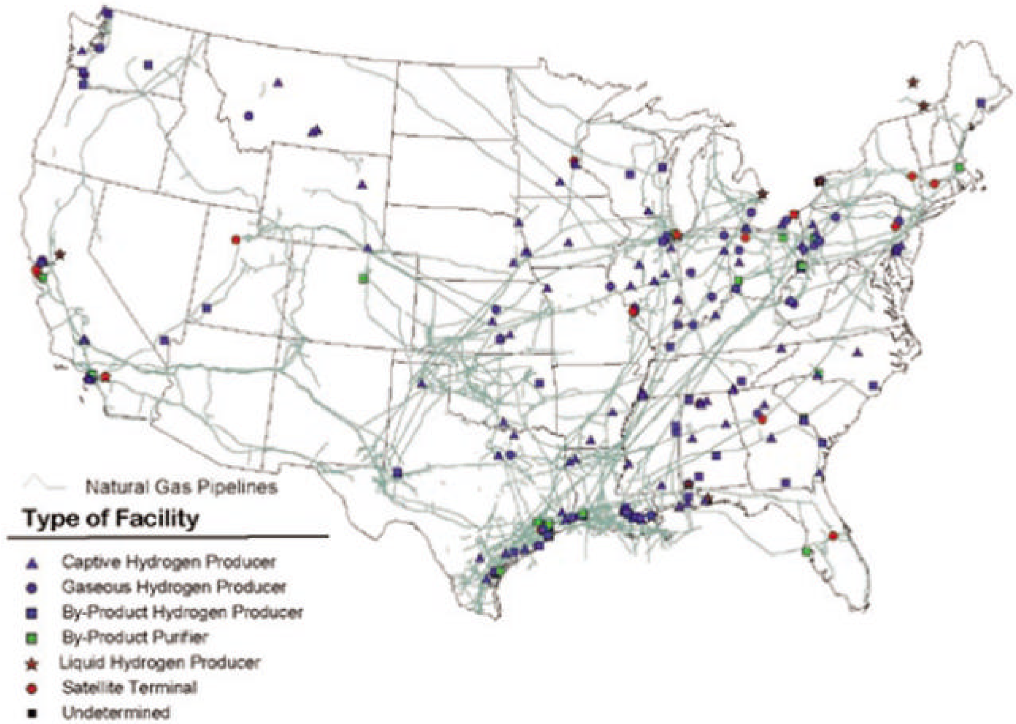

Figure 15: Hydrogen facilities and natural gas pipeline network in the US (Source: Turner et al, 2004)

The fear for sunk costs related to the existing energy infrastructure, could strongly influence how the future hydrogen supply evolves. Since this billion-dollar infrastructure is already there and since companies are trying to protect it, hydrogen from natural gas is locked-in in the development processes. In the long term, when natural gas is expected to play a minor role, parts of the existing infrastructure, like production sites, gasoline stations, and primary research infrastructures, might still remain in use for hydrogen systems and can influence or lock-in certain developments.

As stated before, liquid hydrogen is very unlikely to be a major part of the hydrogen economy because of the costs and logistical problems in handling it and because liquefaction is so energy intensive. Transportation as a gas is more likely. According to Romm (2004b), however, pipelines are unlikely to be the main hydrogen transport means until the post 2030 period. Interstate pipelines are estimated to cost $1 million per mile or more. Yet we have very little idea today what hydrogen generation processes will win in the marketplace during the next few decades, or whether hydrogen will be able to successfully compete with future high-efficiency vehicles, perhaps running on other pollution free fuels. This uncertainty makes it unlikely anyone would commit to spending tens of billions of dollars on hydrogen pipelines before there are very high hydrogen flow rates transported by other means and before the winners and losers at both the production end and the vehicle end of the marketplace have been determined (Romm, 2004b); the before mentioned chicken-egg problem.

Chevron's Rick Zalesky is even more skeptical. According to him "pipelines serve the oil and natural gas distribution very well. Hydrogen is different though. Since the energy content per volume is much lower you need a lot more pipelines. The current pipeline system was built when the U.S. was built. But how do we think we can build all those new pipelines in our existing society?" This reason, together with the enormous space you need for storage at centralized plants, means that Chevron is focusing on distributed hydrogen production, rather than centralized. For centralized production technological breakthroughs for transportation and storage are required, according to Zalesky.[27]

4.3.4 Fuel Cell

As last component I will briefly describe the fuel cell technology. Although the fuel cell does not play a key role in my research, hydrogen and fuel cell technologies are so closely related to each other that it is important to discuss fuel cells as well.

In a fuel cell electricity is produced by an electric-chemical reaction. The chemical energy of the fuel is directly converted into electric energy without intermediate thermic or mechanical processes. This fundamentally differs from most conventional methods of power generation. The fuel reacts with the oxygen and the produced energy results in low voltage electricity (0.7 – 1.2 V[28]) and heat. In a fuel cell vehicle the electric power is used in the electric engine that drives the vehicle. A fuel cell consists of an anode, a cathode and an electrolyte. They are characterized first by the kind of electrolyte that they use and then subcategorized by the type of fuel they use. The two broad categories of fuel cells are acid and alkaline (referring to the chemical nature of the electrolyte) (MacLean and Lave, 2003). Several types of fuels are available for a fuel cell. Of all of the fuels that have been tested in fuel cells, hydrogen has the highest reactivity. In most cases hydrogen is therefore the preferred fuel for use in the present generation of fuel cells being developed for commercial applications (Dicks, 1996).

In a typical fuel cell, hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode, where oxygen is introduced. At the cathode, the oxygen binds with the hydrogen ions to form water. To complete the process, the free electrons released at the anode must join with the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates a current that can be used to power an electric device (MacLean and Lave, 2003). In figure 16 this process is shown.

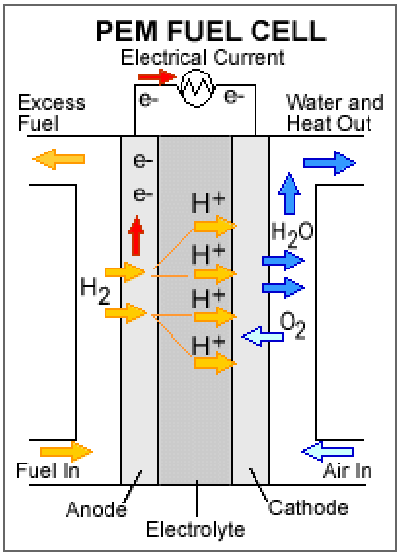

Figure 16: PEM Fuel Cell (EERE, 2006)

Several types of fuel cells are being developed both for mobile and stationary sources; proton exchange membrane, solid oxide, molten carbonate, phosphoric acid, alkaline, etc. Each of the options varies in size, weight, energy output (electrical and heat), cost and other parameters. Fuel cells for transportation must meet more stringent requirements in terms of size and weight limits than those for stationary applications. The

[27] Data from interview with Rick Zalesky, Chevron/Texaco
[28] http://www.cem.msu.edu/~cem181h/projects/97/fuelcell/chem1.htm

leading fuel cell technology for the automotive sector is the proton exchange membrane (PEM) fuel cell. According to the National Fuel Cell Research Center, PEM have greater than 55% efficiency (fuel cell only) when running on hydrogen. PEMs have the following attributes that make them suited to automotive use: they operate at relatively low temperatures (less than 90 ºC); have a high power density and fast response; have safe and easy handling during manufacture and operation; quick startup and shutdown; and maintenance is not expected to be significant (MacLean and Lave, 2003). Matsumoto et al (1997) also think that fuel cells equipped with PEM is the most promising for passenger cars, since the power per unit weight of fuel cell is large; response time is quick; and operation temperature is relatively low.

Fuel cell vehicles can be powered directly by hydrogen stored on the vehicle, or indirectly by extracting hydrogen from onboard liquid fuels, such as methanol or gasoline, in a ‘fuel reformer’. The direct hydrogen fuel cell vehicle is preferred, since it would be less complex, have better fuel economy, lower greenhouse gas emissions, greater oil import reductions and would lead to a sustainable transportation system once renewable energy was used to produce hydrogen (Thomas et al, 1998).

Although there are still many challenges lying ahead, especially when it comes to costs (about $1 million today), fuel cell vehicles are believed to become much cheaper than current vehicles.

Now that the different components related to the hydrogen technology have been explored, promising technologies have been pointed out and expectations about the different technologies are clear, the actual specific niches and the current status and use of hydrogen as a fuel for transportation and the will be explored. The next section will discuss these issues.

4.3.5 Hydrogen Niches

In the previous sections several new promising hydrogen technologies have been discussed. Most of these technologies still only exist in laboratories or in early experimental phases. They are expected to enter actual niche markets sooner or later. The existence of hydrogen niche markets, in which new technologies are protected from normal, mainstream market processes, is very limited. The current niches are mainly technological niches, experimental protected spaces. In this chapter I will have a closer look at existing specific niches and at applications of the technology.

According to Fuel Cells 2000[29] there are 73 hydrogen fueling stations worldwide (Fuel Cells 2000, 2006). Of these 73, 26 stations are situated in the U.S., with 15 in California. Many more stations are planned for the next few years. In figure 17 the worldwide hydrogen fueling stations are shown.

[29] Fuel Cells 2000 is an activity of the Breakthrough Technologies Institute (BTI), a non-profit educational organization formed to promote the development and early commercialization of fuel cells and related pollution-free, efficient energy generation, storage and utilization technologies and fuels. http://www.fuelcells.org/

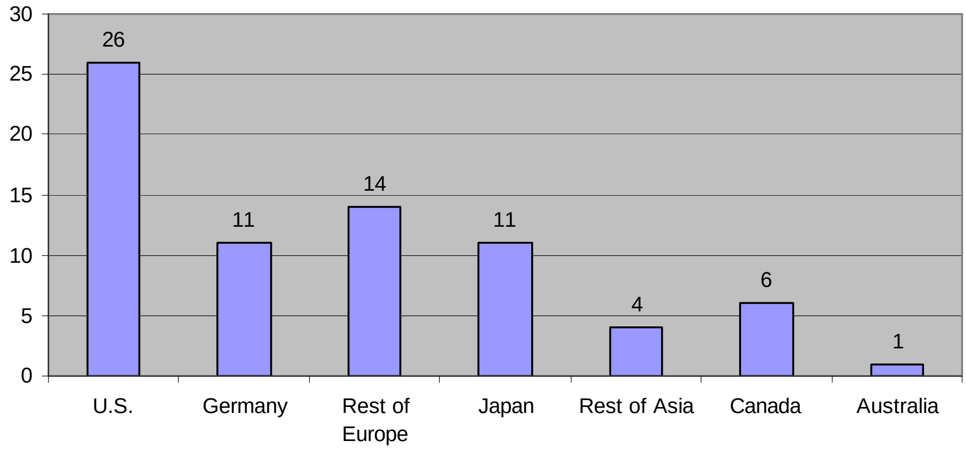

Figure 17: Worldwide hydrogen fueling stations

The first hydrogen fueling station in the U.S. that still operates opened in 1992 in California as a project of the University of California, Riverside. This station made use of onsite solar-hydrogen production. Today 17 stations make use of onsite production, 8 stations get the hydrogen delivered (by truck) and for 1 station it is unknown. The main supplier for hydrogen is Air Products and Chemicals (APCI) that delivers hydrogen to 7 stations. APCI is also involved in 2 onsite production projects. The main actor in onsite production is Stuart Energy, which is involved in 8 projects. Worldwide Linde AG is a third company that is extensively involved in retail ventures (Fuel Cells 2000, 2006). In addition to the major retailing companies, two multinational oil corporations stand out for their involvement in hydrogen energy R&D and reformation technology: BP and Royal Dutch Shell. Shell has committed over $1 billion to hydrogen energy R&D and commercialization activities through 2006, when it believes that the hydrogen vehicle market will have begun (Solomon and Banerjee, 2006).

For 13 of the fueling stations in the U.S. the hydrogen is either produced by reforming natural gas or is a by-product from industrial processes. 12 stations produce hydrogen by electrolyzing water and for 1 station the situation is unknown. All the hydrogen that comes from APCI is based on reforming natural gas or is a by-product. Stuart Energy only makes use of electrolyzes of water. At least 5 of the 12 ‘onsite production stations’ make use of renewable energy to generate the electricity needed for producing hydrogen. At 20 stations hydrogen is stored as a compressed gas, while only 5 stations store it as a liquid. One of the stations has both. Apart from one, all the fueling stations that store liquid hydrogen transform it back to gas again at the pump, since most vehicles require the compressed gas (Fuel Cells 2000, 2006).

The 26 hydrogen fueling stations in the U.S. are mainly build for the purpose of test programs or demonstration programs with, for example, city buses. Six fueling stations serve bus demonstration projects and fuel in total 16 buses. Nineteen of the projects serve either a test program from car manufacturers or a demonstration program – or small niche – like, for example, a UPS fleet in Ann Arbor, Michigan and the airport vehicle fleet of Los Angeles International Airport. Most test and demonstration programs involve fuel cell cars or minivans or small ‘neighborhood vehicles’. Finally, there is one fueling station located at the University of California, Riverside and one station serves the U.S Navy. These specific ‘vehicle niches’ are actually more related to the transportation regime than to the petroleum regime, but both regimes are very closely linked to each other. The hydrogen production and distribution technologies and niches are specifically related to the petroleum regime.

Since 2000, the members of the California Fuel Cell Partnership – among them the main car manufacturers – have placed 134 light duty vehicles in California, and traveled over 420,000 miles on California’s roads and highways.[30] The coming years California plans to realize the Hydrogen Highway, a plan initiated by the State and announced in April 2004 by governor Arnold Schwarzenegger. Over a 100 fueling stations are planned to be built before 2010.[31] The niche markets will thus grow in number significantly coming years. The same technologies are expected to be applied for these new fueling stations.

The activities and used technologies in the niches obviously confirm the expectations and promises described in the previous sections. Natural gas reforming and electrolyzing water, as stated before, are the main technologies that are applied. Renewable sources are only used for a few projects. Obviously hydrogen is not yet distributed by pipelines, since demand is too small; onsite production is by far the most chosen method. Hydrogen storage as compressed gas is far more popular than storages as a liquid, both at the fueling station, but also onboard the vehicles.

Since the market niches are so few and small today, the pressure from these niches on the existing regime is very limited, if there is any pressure at all. The technologies are still very expensive and have not proven themselves yet. In the future many ‘promising’ technologies from the previous sections are expected to enter niche markets as well and as soon as technologies become more diffused, more pressure will probably be put on the regime. In the next section I will further analyze the processes that influence the development of ‘promising’ technologies and their possible successes; the processes of variation and selection.

4.3.6 Co-evolution

As became clear from the previous sections, there are many ‘promising’ hydrogen production technologies that can play an important role in a future hydrogen economy. Promising technologies are, however, no guarantee for successful implementation and exploitation. Many promising technologies failed to eventually enter the market, or could not deal with market forces once the market was entered. Electric Vehicles and Natural Gas Vehicles are only two examples of a wide arrange of ‘promising’ technologies that did not make it. Promising technologies play an important role in technological developments; they influence research efforts and budgets and steer the development in certain directions.

The fact that hydrogen can be produced from a wide array of energy sources results in the many technological options, or *variations*, that can be pointed out. This is in contrast with our existing transportation regime where the technological options are more concentrated; gasoline can basically only be made from oil and oil needs to be extracted

[30] http://www.fuelcellpartnership.org/fuel-vehl_cars.html
[31] http://www.hydrogenhighway.ca.gov/

from oil fields[32]. As the technological developments continue, some variations will appear to be more promising and applicable than others. This can result in the rise of one dominant technology, or in a few technologies existing next to each other.
If a certain technology has the potential to become dominant does not only depend on the characteristics of the technology, but also on the selection environment, the context. The way the changes at the landscape level put pressure on the existing oil regime and create possibilities for hydrogen, the same way these changes shape the selection environment. The existing oil regime caused problems related to the environment, economy and energy security. This drastically has changed the selection environment, which has an influence on the new developed technologies again. This process of co-evolution has been discussed in section 2.3.

Schot (1992) makes a distinction between ex post-selection and ex ante-selection. Ex post-selection is the process in which technological variations are exposed to the selection environment after the development. This is what happens in the niches that were discussed in section 4.3.5. In the niches it is not merely the goal to expose the technology to the market, but also to several institutional and societal factors. In niches the selection environment is manipulated to protect the technology or to give it a chance to develop. Ex ante-selection is the process in which the selection environment influences the actual generation of technological variations. Anticipation, both on the selection environment and on emerging patterns as mentioned in section 2.3, is a key issues in ex ante-selection.

Ex ante-selection is clearly visible when it comes to hydrogen technologies. Developers take into account the existing and supposed future selection environments. According to Debbi Smith from NHA, energy companies, for example, recognize that there is a need to look at different energy sources for the future, both because of business reasons – markets will change eventually and the commodity on which their business is based will most likely not be there sooner or later – and environmental reasons. Patrick Serfass adds that “the thing energy companies hate the most is their dirty reputation. Renewables and clean technologies gained more interest because of your company. So, energy companies want to change that reputation, but they are also concerned about the bottom line.” Sir Moody-Stuart, former chairman of Shell indeed stated: “We want to meet our customers’ needs for energy, even if that means leaving hydrocarbons behind” (Vaitheeswaran, 2003). That forward-looking notion of seeing his business as delivering energy, rather than just petroleum, was echoed soon thereafter by BP, which launched a big advertising campaign declaring itself “Beyond Petroleum”. Though oil and gas remain their main business, both firms have started investing in long-term prospects like renewables and hydrogen energy (Vaitheeswaran, 2003). Chevron/Texaco has similar incentives to put efforts in the hydrogen development. According to Jim Stevens, Catalyst Program Manager of Chevron Technology Ventures, Chevron/Texaco is working on hydrogen technologies to protect their business. Hydrogen is one of their bets and to keep the future options open they want to gain knowledge about the several aspects of a hydrogen economy. Therefore they spend $24 million a year on hydrogen. Rick Zalesky states that “Texaco began working on hydrogen in the late 1990s, because they recognized the need for a solution for the carbon dioxide problems. In addition to that,

[32] Of course there are several technological options for gasoline production and oil extraction, like the recently more used tar sands and deep water technologies. This example, however, only serves as an illustration of the wide arrange of sources and variations that can be used for hydrogen production.

societies demand more energy in the future and we cannot continue with oil and natural gas. Hydrogen from natural gas is one of the possible pathways for fuel, but so could be solar, geothermal, ocean currents, wind. Societies need energy and we as Chevron/Texaco have to make sure we can supply it."

Anticipation is not only related to market and environmental aspects, but also to existing legislation and expected future legislation like carbon taxes, for example, can influence the developments. Royal Dutch/Shell, for example, decided that all big projects must take into account the likely future cost of CO2 emissions. Shell's Aidan Murphy explained: "We know that $5 and $20 are surely the wrong price, but everyone else who assumes a carbon price of zero in future will be more wrong. This is not altruism. We see it as giving us a competitive edge" (Vaitheeswaran, 2003).

Finally, developers also anticipate on the developments of and expectations about technologies. According to Vaitheeswaran (2003), the reason that 'Big Oil' turned towards renewables and hydrogen is, whatever their clever advertising campaigns say, not because they suddenly decided to worry about the environment. The real reason is that recent technical advances have been so promising that the incumbents simply could not ignore hydrogen any longer. One oil boss explains: "fuel cells have produced more technological breakthroughs in five years than battery research has in the past thirty" (Vaitheeswaran, 2003). The technology is expected to become important in the future and the advances are so great that market incentives, not mere regulation or environment, are now motivating them. Whatever the true reason is, it is clear that industries, with their technological developments, anticipate on existing and future selection environments.

Apart from anticipation, the technological nexus also plays an important role in variation and selection processes. This will be discussed in chapter 5.

When it comes to hydrogen, the end-game is not clear yet and most experts think it is too soon to tell what technologies will dominate the hydrogen production. The processes of variation and selection still evolve and the winners are not clear yet. However, renewable energy sources are, in general, considered to be the ultimate goal and the main source of the future. This is only for the very long-term. At this moment renewable energy has not been developed well enough and the markets are still too small. Moreover, hydrogen produced by renewable energy sources is not cost-effective yet. For the medium term, coal and nuclear are expected to play a major role.

For the short-term hydrogen from natural gas seems to be the winner. This technology has proven itself already and is most cost-effective. Developments in the past determine, or at least influence, future developments; future developments follow the technological path that has already been pursued. This path dependency, or lock-in, is most obvious in the case of natural gas. The fact that this technology has proven itself already is not the only factor that determines the path. As we will see in the next chapter, the power and actions of the industries that may fear sunk costs in their existing (natural gas) infrastructure – the existing regime – plays an important role. This does not mean that new technologies do not have a chance, but they have to 'fight' the existing regime as is explained in chapter 2.

Although the different actors all try to make sure that they will play a significant role in a future hydrogen economy, they all acknowledge that hydrogen will come from different sources. The expectations are that there will be a mix of energy sources, depending on the available sources in a certain area, the demand in a certain area, etc. According to Maria Curry-Nkansah, Hydrogen Project Manager of BP, BP therefore pursues "multiple feedstocks." "Hydrogen production depends on the region. If there is a lot of natural gas in a region, then natural gas will probably be the source, but if the potentials for solar power are high, then this can be a source. Not one pathway is *the* pathway." Thus, several variations are expected to become winners and will exist next to each other.

Anticipation plays an important role in variation and selection processes, and expectations seem to be a key factor related to anticipation. As this section addressed, expectations about technologies, future markets, future legislation, etc. influence the co-evolutionary processes. In the next section I will further analyze the role of expectations.

4.3.7 The Role of Expectations

As became clear from section 4.3.6, expectations and promises play a crucial role in early phases of technical development and in the creation of niches. They have a great influence on the direction of technological developments. This is not only related to anticipation from developers, but also from governments and other involved organizations.

As discussed in section 2.6, Van Lente and Rip (1998) distinguish three emerging patterns in expectations about technology. Two of those can be seen in the hydrogen developments: self-fulfilling prophecy and the self-justifying technology. First, as we have seen, the developments of hydrogen technologies are influenced by expectations about technologies, markets, etc. and because of this influence, the expectations themselves are at the same time supported. Actors take up the expectations or prophecy and act accordingly, it is a self-fulfilling process. Second, like the HDTV, hydrogen can be seen as a self-justifying technology. Hydrogen is the subject of a strategic game and the economic and political interests associated with hydrogen and FCVs are immense. The market is a billion dollar market and one's market share will have important consequences for other industrial activities, for the labor market, and for the relative strength of national economies. It is only because hydrogen and FCVs are taken as promising that there are interests at stake, and that interest politics can come into play. Obviously, this would not be the case if the technology was not promising and expectations were low.

Apparently the expectations about hydrogen create '*prospective structures*'; actions become coordinated through the prospect of a new technology and its functions while this emerging configuration is simultaneously shaping the technology to be. As Van Lente and Rip stated, expectations indeed contain a 'script', indicating promising lines of research and technical development to be undertaken by the enunciator of the statement and/or by others. These scripts are not followed automatically, but are the result of the actions and interactions of technologists, firms and governments. In chapter 5 the role of actors and their expectations will be further analyzed.

Regardless of the fact that a technology is still in the early development stage, the prospective structures, created by expectations and promises, put a significant pressure on the existing regime due to the perceived implications of the projected future. The forces on regimes, thus, already start far before niches are created and therefore play an important role in the process of technological change.

4.3.8 Technology Foresight

In this final section of this chapter I will, based on the previous sections, give a technological foresight. Many aspects and likely future developments are mentioned already before, so this section serves partly as a summary as well. First, an overview of the different technological components and technologies is shown in table 2.

Table 2: Summary of hydrogen related technologies

	Advantages	Problems	Script	Expectation
Energy Source				
Natural Gas	- Proven technology - Cost effective - Wide availability - Easiness to handle - High hydrogen to carbon ratio	- Expected to peak soon - Foreign source	Macro, meso and micro	Near term/ Transition
Coal	- Cheap - Domestic reserves	- CO2 - CCS needed; im-mature & uncertain technology	Macro	Medium and long term
Nuclear	- No emissions - Domestic	- Image - Waste - Safety - Security - Costs	Macro	Medium and long term
Electro Lysis	- Well suited for transition - Well suited for renewables	- Costs	Macro, meso and micro	Transition and long term (in combination with renewables)
Wind	- Clean - Domestic - Infinite - Most competitive renewable	- Siting - Environmental - Technology - Intermittence - Costs	Macro and meso	Minor role in near term, but large role in long term
Bio mass	- Domestic - Renewable	- Space - Intensified use of cropland (fertilizers, erosion, etc.) - Costs	Macro	Not likely to play a significant role
Solar	- Clean - Domestic - Infinite	- Costs - Technology - Intermittence	Macro, meso, and best solution for micro	Long term
Storage				
Gas	- Costs - Widely used - Simple technology	- Space	N/A	Most likely for near term and maybe longer
Liquid	- Easy to handle - High energy density	- Costs - Energy intensive		Not likely
Hydrids	- Space - High energy density	- Complex - Immature		Breakthroughs needed to make it
Distribution				
Pipe Lines	- Good for large amounts and long distance	- Costs (compared to fossil fuels) - Costs (of infra) - Space - Impact on society	N/A	Very likely when hydrogen demand is large enough
Trucks/	- Good for limited range and	- Not suitable for		Likely to play a role in

Trains	demand - No expensive pipeline infra needed	large amounts - Costs		near term and for places where demand is low
Gas	- Costs (compared to liquid)	- Space		Most likely mode of transportation (in combination with pipelines)
Liquid	- Easy to transport - High energy density	- Costs - Energy intensive		Not very likely
Fuel Cell				
PEM	- High efficiency - High power density - Fast response - Safe and easy handling - Maintenance - Low operation temperature	- Costs - Immature	N/A	Very likely

Most scientists, engineers and other involved actors from industries, governments, NGOs, universities, environmental organizations, etc. are convinced that the hydrogen transition will happen. A lot of progress has already been made and several new promising technologies are being developed and demonstrated right now. As Patrick Serfass, Director Program and Technology Development from the National Hydrogen Association, states it, "the question is not if it will happen, but when."[33] Bill Ford – Ford's chairman and the great-grandson of the company's famous founder – is positive as well and believes that "…fuel cells will finally end the hundred year reign of the internal combustion engine" (Vaitheeswaran, 2003)

Not everyone is so optimistic though. Gary Gray, a senior research engineer at Georgia Tech Research Institute, expects that hydrogen will only make it into a few more niche markets and in some specific places where clean energy is needed. He thinks that eventually hydrogen will count for only a few percentages of the total energy supply.[34] Jim Stevens, Catalyst Program Manager at Chevron Technology Ventures, is sceptical as well and thinks that higher efficiency cars and biofuels have a bigger chance for the future.[35] Ron Larson from ASES, who is more intrigued by higher efficiency cars, especially plug-in hybrids, and biofuels as well, does not agree with Jim Stevens. He stated that "the power of the industries will dictate the developments. The automotive companies in Detroit *[the big three: GM, Ford, DaimlerChrysler]* did not endorse hybrids and biofuels, but favor hydrogen fuel cell cars."[36]

The actors that think that the hydrogen transition will happen do not have a clear answer on the question when it will happen. The general perspective is, however, that it will not happen within the next two decades. A recent National Research Council (NRC) report suggested that under an optimistic timetable, hydrogen-fueled vehicles could replace light-duty vehicles by 2050. But that would require about 111 million tons of hydrogen per year – more than 12 times current production levels (Newell, 2005). Figure 18 shows the hydrogen timeline as proposed by the U.S. Department of Energy (DOE).

[33] Data from interview with Patrick Serfass, NHA
[34] Data from interview with Gary Gray, Georgia Tech Research Institute
[35] Data from interview with Jim Stevens, Chevron/Texaco
[36] Data from interview with Ron Larson, ASES

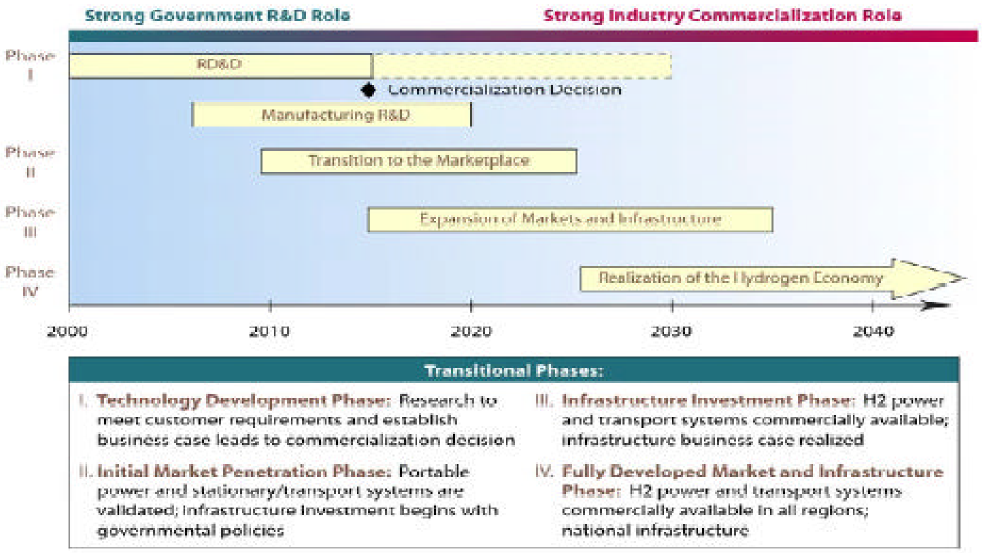

Figure 18: Hydrogen economy timeline with manufacturing R&D (DOE, 2005)

For the coming decades, when hydrogen and FCVs will enter the markets, natural gas reforming will probably be the main production method, since it is the most cost-effective and mature technology. This is expected to change, however, because of expected increases in gas prices and the rise of new production technologies. Gas production is expected to peak within one or two decades, which will change its favorable conditions for hydrogen production. Meanwhile, hydrogen from coal, and to a lesser extent hydrogen from nuclear, are expected to gain market shares. Hydrogen from coal will probably be the cheapest source and is expected to gain a significant market share when the technology – especially the CCS technology – is developed sufficient and the favorable conditions for natural gas change. The technology is expected to be demonstrated within one decade. Interest in nuclear energy has been risen again the last couple of years. However, it still faces some major problems and has a bad image. It is therefore difficult to tell how the nuclear industry will develop in the future. New technologies, however, seem promising and nuclear hydrogen is also expected to produce a significant amount of hydrogen in the future. Finally, renewables are expected to play an important role only in the far unforeseeable future. Using renewables for hydrogen production is the most desirable scenario, since it can be a solution for all three changes at the landscape level; it is clean, domestic, and infinite. These production technologies are still very expensive and not competitive, however. Hydrogen from wind is most cost-effective and is expected to play a minor role in the near future. Hydrogen from solar is very promising and it has the potential to become the main hydrogen production method in the next century. Altogether it is not expected that hydrogen will come from one energy source; it is more likely that a mix of energy sources will produce our future hydrogen.

The tendency towards coal and nuclear hydrogen implies that centralized production will be the main production method for the future, since both production methods contain a 'macro script'. This, again, implies that an extensive hydrogen distribution system is required. In the near term it is very unlikely that a pipeline system will be realized, but when demand increases, which is expected by the time that coal and nuclear 'take over', pipelines are seen as the best means of distribution. Until then, either decentralized production or trucks and trains will be applied.

Hydrogen will be stored as compressed gas as long as other, better means of storage are absent. This applies both for onboard storage as 'on land' storage. This implies that centralized plants need a lot of space for hydrogen storage. Liquefying hydrogen is too expensive and energy intensive and storage technologies that involve metal or chemical hydrides are not well-developed and cost-effective yet.

4.4 Conclusion

Hydrogen is a very promising fuel for the future. Its abundance, energy content, potential to be a pollution free fuel, and the fact that it can be produced from a variety of (domestic) energy sources, make hydrogen an interesting option for substituting oil and driving our future economy. Although the 'Hydrogen Economy' is getting more and more popular, hydrogen is not a new product, recently developed. The first practical use goes back to an army camp in Paris in 1794 and today hydrogen is used in industries as a chemical factor at large scale. Hydrogen was first exploited as a fuel in aviation in German Zeppelins in the 1920s and 30s. Interest in hydrogen as a fuel rose significantly in the 70s during the oil crisis, decreased again after the oil crisis and then in the 90s interest rose again, but this time because of environmental reasons.

Today three important aspects that put pressure on the petroleum regime – the regime that plays a key role in the hydrogen transition and is the main focus of my research – can be seen. These are environment, peak-oil, and geopolitics, with energy security as the main concern related to oil. These issues put pressure on the regime from both the landscape level, as from within the regime itself and the problems related to these three factors can, in general, not be solved within this regime. These pressures influence the development of technologies embedded in regime as well as new promising alternatives by creating the 'windows of opportunities' for the development and implementation of hydrogen technologies.

Many different promising hydrogen production technologies are being developed from a wide variety of energy sources and put pressure on the regime level from the micro level. These production methods each contain a certain script regarding centralized and decentralized production. I have distinguished three scripts: macro-production, meso-production and micro-production. The importance of these scripts is that the different production methods imply certain infrastructures. This will have its influence on the distribution systems and on society in general, as will be discussed in chapter 6. Some of the hydrogen technologies are being tested in market niches already. These niches are, however, very small and limited. Most pressure on the petroleum regime is caused by the articulation processes regarding promises and expectations about technologies. These expectations show a self-fulfilling and self-justifying process and hydrogen became the subject of a strategic game. Expectations and promises related to hydrogen create '*prospective structures*'; actions become coordinated through the prospect of a new technology and its functions while this emerging configuration is simultaneously shaping the technology to be. I will come back to this in the next chapter.

The fact that hydrogen can be produced from a wide array of energy sources results in the many technological options, or *variations*, that can be pointed out. It is too early to tell which variation(s) will become the dominant technology(ies), but most likely hydrogen will come form multiple feedstocks. In the development of variations, path dependence is best noticeable in the case of natural gas. This technology has proven itself already and is most cost-effective. It is seen as the main technology for the coming decades and most existing fuelling stations make use of this production method. Apparently, the developments in the past determine, or at least influence, future developments; future developments follow the technological path that has already been pursued.

If a certain technology has the potential to become dominant does not only depend on the characteristics of the technology, but also on the *selection* environment, the context. During the development of variations, hydrogen technology developers try to anticipate on the present and future selection environment. Four aspects seem to play a role in the anticipation process related to hydrogen developments are: market; environment (including 'dirty reputation'); legislation; and developments of and expectations about technologies. The different hydrogen technologies and the expected infrastructure are summarized in section 4.3.8.

In the next chapter I will analyze the actors involved in the hydrogen transition, their interests, actions and positions. In that chapter I will focus on social mechanism and as mentioned before, the role of a technological nexus and the actions and interactions of actors related to expectations will be analyzed.

5. Hydrogen's Social Environment

In technological developments and transitions, many actors are involved. This especially applies for the hydrogen transition, because of the many different technologies, and thus technological developers, that can play a role. All actors have different roles, interests, views, expectations etc. related to the transition and (can) try to influence the process to create a favorable future for themselves, or for society. Potential new hydrogen producers try to put pressure on the existing petroleum regime, while the actors in the petroleum regime also try to influence the transition, either by slowing down the process, or by dictating it. Apart from developers, environmental organizations, users and the government are also involved in the transition. In this chapter this social environment of the technology will be analyzed. This is the second step of the CTA. In the social environment the articulation of promises and expectations by actors, the role of other social mechanisms and of users, play an important role as we will see.
In section 5.1 the different relevant organizations, institutes, societal groups, etc. that play a role in the hydrogen transition will be described. Section 5.2 is a more in depth analysis of how each actor (group) influences the developments. In this section a continuation of the in chapter 4 discussed co-evolutionary processes will also be given.

5.1 Actors

In this section the different relevant organizations, institutes, societal groups, etc. that play a role in the hydrogen transition will be described. The actors will be introduced briefly and the main focus is on primary actors. In section 5.2 the positions and influences of the actors and the secondary actors will be explored. In their CTA method Smit and Oost (1999) have distinguished four different actor groups: technology regulators; technology developers; technology users; and other groups. I will discuss each group, and their role in the hydrogen transition, in this order.

5.1.1 Technology Regulators

Local, national and international regulators play an important role in the energy and transportation sector. The two main ways of influencing developments are regulation and funding. With regulations governments aim to decrease emission of greenhouse gases and pollutants for example. As has been discussed earlier, economy and geopolitics can be drivers as well for governments to regulate or stimulate certain technologies. With regulations the development and use of certain technologies can be supported, while the development and use of others can be impeded. Local governments can stimulate the use of hydrogen in buses for example by demanding a certain amount of use (e.g. ten percent of the buses should be hydrogen buses in 2010). For private use, regulations like this are much more complicated at a local level, because vehicles are mobile; if one city or state prohibits the sale of conventional cars, car manufacturers can sell them in another city or state and will move away their activities. Besides, the auto and oil industry have a lot of power to thwart regulations. Regulations on a national or even international level are therefore necessary.

Governments can also steer and stimulate technologies by funding and subsidizing R&D projects or certain technologies. In the U.S. at the federal level the most important actor related to hydrogen, and energy issues in general, is the *Department of Energy (DOE).* In addition to DOE there are several committees in the Senate and House of Representatives that are involved in hydrogen technologies. Examples for that are the U.S. Senate Committee on Energy and Natural Resources and the House Committee on Science. These Committees take a comprehensive, thoughtful look at energy policies and can influence politics. In 2003 the federal government started to heavily support and stimulate the transition to a 'hydrogen economy', when President Bush called for $1.2 billion to be spent on hydrogen research; the Hydrogen Initiative was born. Since then, interest in the hydrogen transition rose significantly and the government, as well as industries, started to spend a lot of money on it.

At state level, there are several states that pursue a hydrogen economy even more than the federal government. *California* is pursuing a hydrogen economy most progressively and is working on the first Hydrogen Highway in the U.S. "The goal of the California Hydrogen Highway Network initiative is to support and catalyze a rapid transition to a clean, hydrogen transportation economy in California […] We have an opportunity to prove to the world that a thriving environment and economy can co-exist" says Governor Arnold Schwarzenegger.[37]

5.1.2 Technology Developers

There are roughly three kinds of technology developers. The government, as described above, independent institutes and universities, and the industries. *Research institutes and universities* play an important role in the development of new technologies. New promising technologies often start in research institutes and universities. Many different research institutes, national laboratories, universities, etc. are involved in hydrogen R&D. For the past several years a large amount of literature has been produced by the scientific community, both supportive and dismissive. Some of the influential institutes and universities related to hydrogen research and the political debate are the National Renewable Energy Laboratory (NREL), Princeton University, University of California, Davis, Rocky Mountain Institute, Argonne National Laboratory, Oak Ridge National Laboratory. Many of these institutes and laboratories are funded by the government and the government is therefore not only a technology regulator, but also a technology developer.

The possible future suppliers of hydrogen play an important role in the development of hydrogen production methods and of distribution systems. These actors are mainly from the *energy industry* like oil and natural gas companies, electricity utilities, nuclear companies, coal companies and renewable industries. These companies work closely together with the research institutes and the government and they have a strong influence on the developments.

The *oil industry* is, with a value between $2 trillion and $5 trillion, the largest business in the world. For most countries, oil is the largest item in their balance of payments; oil counts for 40% of the energy demand in the U.S. Due to several merges in the years 1999 and 2000 "super major" energy companies were created and today only a few companies control the energy flow through the economy (Rifkin, 2002). "Therefore

[37] http://hydrogenhighway.ca.gov/

the companies are in a unique position to dictate the terms of doing business for all of the other enterprises that make up the industrial mix. In a domestic and global economy that is increasingly controlled by fewer and fewer big corporate players in every industry and field, the energy companies are ensconced on the very top of the global pyramid, dispersing the energy that keeps every other economic activity going" (Rifkin, 2002).

In addition to the capital strength of the major oil (and energy) companies there is another characteristic that distinguishes the energy industry. The energy industry uses more varied technology and specialized personnel than any other industry. This applies both for the technical activities as for management and marketing activities (Rifkin, 2002). Their size, capital strength, power to control most industries, and expertise in the energy market gives the oil industry a very strong position in a future hydrogen market and their influence on the developments is very strong.

Although not as big and influential as the oil industries, the *coal industry* and the *electricity utilities* play a significant role in the energy distribution, and more general in society, in the U.S. as well. 22% of the energy consumed in the U.S. comes from coal (EIA, 2004), mainly for the generation of electricity. Coal has a huge advantage compared to oil and natural gas when it comes to future energy supply. The coal reserves are much larger and can probably serve us sufficient throughout the 21st century. Moreover, the coal reserves are mainly situated in North America, Europe, Eurasia and Asia Pacific. Therefore the coal industry is likely to strongly influence future developments as well.

Although no new nuclear power plants were ordered in the U.S. since 1978, and no new nuclear plant was finished since 1995 (Lake et al, 2002) [still applies for 2006], the *nuclear industry* is gaining more support again and new Generation IV reactors are expected to be built within a decade. With 103 reactors, nuclear power counts for 20% of the electricity in the U.S. (Lake et al, 2002). Since nuclear power causes no carbon dioxide emissions and is a domestic energy source, nuclear-hydrogen is, as discussed in chapter 4, expected to play an important role in the hydrogen economy. Therefore, nuclear industries have an influence on the developments.

The *renewable industry* is the smallest energy industry in the U.S. and counts for about 6% of the total energy consumption (EIA, 2005b). In the year 2000 renewable energy already counted for 6%, so despite all efforts, the renewable energy industry in the U.S. is growing really slow (EIA, 2005d). Today biomass and hydroelectric power are the main renewable sources with 47 and 45% respectively (EIA, 2005b). When it comes to hydrogen, however, wind and solar are considered to be the most promising sources.

Although new U.S. installations have been growing slowly compared to rapid advances in several European countries, U.S. wind generating capacity rose from 1.039 GW in 1985 to 2.554 GW by the end of 2000 and since then, the capacity rose fast (Smil, 2003; AWEA, 2006). In 2005 the cumulative U.S. installed wind power fleet was boosted by over 35%, bringing the industry's total generating capacity to 9,149 MW. Installations are expected to top 3,000 MW in 2006 (AWEA, 2006). These rapid growths of the wind market make wind one of the fastest-growing energy sources. Despite the increases in wind energy, the industry is still very small and wind energy accounts for only 1-2% of total energy consumption. Therefore, their role in hydrogen production and their influence on the developments is very limited today, but will become more significant in the future.

Solar energy, with less than 1% of total energy production in the U.S. is less successful yet, but significant growth is visible. Worldwide annual shipments of PV cells and modules reached 0.5 MW of peak capacity (MWp) in 1977 and in the year 2000 cumulated installed capacity amounted to about 500 MWp in the United States and almost 1 GWp worldwide (Smil, 2003). More recent numbers from the ABS Solar PV Report 2006 show that the overall growth in the solar photovoltaic sector has been robust indeed, and by 2007 production capacity could reach 5,000 MW (ABS, 2006) Like wind, the role of solar energy in hydrogen production and their influence on the developments is very limited today, but will become more significant in the future.

To conclude, the oil industry, by far the most powerful and influential industry today, is likely to remain a big player in a future hydrogen market. However, coal, nuclear and renewable industries have high potentials to compete with the oil industry and to gain significant market shares.

5.1.3 Technology Users

As became clear in chapter 4, there are already a lot of users of hydrogen, primarily in the chemical industries. When it comes to hydrogen as a fuel for transportation, *car manufacturers* are the main user of the technology. As has been said before, hydrogen and fuel cell technologies are closely linked to each other, and hydrogen is expected to be used in future vehicles. Car manufacturers therefore are likely to be an important actor in the hydrogen transition.

Hydrogen vehicles will, at first, be of use for *fleet companies*. As long as a decent infrastructure is absent, the technology is only useful for vehicles with a limited range or vehicles that stay relatively close to a supply station. Here we can think of taxi fleets and public transportation companies. Especially for buses the technology is, at first, useful, because large tanks for the storage of hydrogen can be put on top of the roof. These companies employ drivers and transport people, who are the *end-users*. When the technology is further developed and commercialized, and when the infrastructure is improved, it also becomes an alternative for *transportation (cargo) companies* and *private users*.

Fleet companies or end-users can influence the hydrogen transition in two ways. First of all, developers have a general image of the user, which plays an important role in the design and development of the technology. Second, users influence the development by means of the market principle. On the one hand the market can create a demand for certain (clean, oil independent, etc.) technologies, with which developers comply. This is called the market pull mechanism. On the other hand, if prospective end-users are not interested in the technology, and do not want to use it, hydrogen does not have a future in road transportation. I will get back to this in section 5.2.5.

5.1.4 Other Involved Groups

Other involved groups that are relevant to be pointed out related to the hydrogen transition are environmental organizations, interest groups and non-users.

Environmental organizations, like Environmental Defense, the National Resources Defense Council, and the Sierra Club, have an interest in technologies that can have a positive impact on environmental issues, like air quality and global warming. Certain hydrogen technologies have the potential of doing that and they might be advocated by environmentalists. Environmental organizations can influence the development of the technology only indirectly, for example by trying to influence and convince governments or companies, or by increasing public awareness.

Interest groups look after the interests of groups of individuals or organizations. This can be, for example, a trade union for the taxi drivers. Their influence is also indirect. A very important interest group for the hydrogen technology developers is the National Hydrogen Association (NHA). In section 5.2 the role of the NHA will be discussed in more detail.

Non-users can also be influenced by hydrogen, for example by increase of prices of conventional vehicles, by decrease of fossil fuel tank stations, or by safety issues. Their influence on the development of the technology is indirect by means of the market principle or by influencing governments and developers. This can be done, for example, by public actions like demonstrations.

To sum up, technology regulators, developers, users and actors like environmental organizations, interest groups and non-users, all can play a role in the hydrogen transition. Their influence and power differs a lot and can be direct or indirect. Now that the different primary actors have been introduced briefly, I will further explore their positions, influences, mutual relations and the secondary actors that have been created in the following section.

5.2 The Actors' Positions and Influences

All actors have different roles, interests, views, expectations etc. related to the transition and (can) try to influence the process to create a favorable future for themselves, or for society. This section gives an in depth analysis of how each actor (group) influence the developments. The way in which potential new actors try to put pressure on the existing regime, the articulation of promises and expectations, the role of other social mechanisms and of users, are key aspects of this analysis. Moreover, the actions from actors in the existing petroleum regime to influence the transition process will get special attention. I will end this section with a continuation of the in chapter 4 discussed co-evolutionary processes.

5.2.1 The Big Energy Industries

Although fuel cells and hydrogen as a fuel were seen as promising long time ago already, and the phrase "hydrogen economy" was introduced in 1970, it was not before the late 1990s that automotive and oil companies, after research institutes and small companies, started to articulate promises and raise expectations about the technology. The automotive industry, or at least an important slice of it, started to see fuel cells, which developments made more and more progress as was especially shown by Ballard Power Systems, as its inevitable and desired future. The oil industries, that today often characterize themselves as "energy companies", followed and started to see hydrogen production as a profitable future market. They realize that the oil market will reach its heyday, and unlike battery-electric vehicles, in which they saw no business case for themselves (Sperling and Ogden, 2004), they can play a key role in a hydrogen economy.

The articulation of promises and expectations – or stories – can happen in different ways. A clear example of how industries articulate their expectations is the release of the well-known "Shell Global Scenarios". For over 3 decades Shell has developed and released Global Scenarios to "cast light on the context in which the Group operates, to identify emerging challenges and to foster adaptability to change" (Shell, 2005). Other ways of articulating expectations are press releases, publications, public statements and speeches, etc. Also the forming of partnerships and coalitions can be seen as a kind of articulation.

With the car and oil industries, expectations and promises were now shared among the two most influential industries in the transportation sector and the articulation of expectations created the prospective structure that was mentioned in chapter 4. These stories and structures created new patterns and institutions and the promising technologies were taken up in the industries' agendas. This does, however, not necessarily mean that the car and oil industries are truly committed to FCVs and hydrogen. Their focus and interest can also be seen as a more strategic move. Car manufacturers and oil companies are eager to show that they are working on environmental friendly technologies and in August 2003, General Motors said that the promise of hydrogen cars justified delaying fuel-efficiency regulations (Romm, 2004). Moreover, FCVs were also considered to be a strategic competitor of the fuel efficient cars from Asia. Even if it is a strategic move instead of a true commitment the prospective structures and a 'hydrogen hype' can, nevertheless, suck these companies more and more into the developments and can influence their actions and other strategic games.

Industries started to join and form groups and partnerships and even established subsidiary companies. In 1999, oil companies and automakers began attending the meetings of a group called the National Hydrogen Association (NHA). Founded in 1989 by scientists from government labs and universities, the association was a haven for many of the small companies – fuel-cell designers, electrolyzer makers – that were dabbling in hydrogen power. The group promoted the use of hydrogen but was careful not to take any position on who would make the fuel or how (Lynn, 2003). That year BP, Shell and Chevron/Texaco also formed, together with Ballard Power Systems, DaimlerChrysler and Ford Motor Company, California Air Resources Board, and California Energy Commission the California Fuel Cell Partnership. Today the California Fuel Cell Partnership is a collaboration of 31 member companies who are working together to promote the commercialization of hydrogen fuel cell vehicles.[38] In 2000, Shell established, after Shell Renewables in 1997, Shell Hydrogen. Texaco purchased a 20% stake in Energy Conversion Devices, a Detroit-based photovoltaic, battery and fuel-cell company, and BP is investing $500 million in renewables over three years (Lynn, 2003; Motavalli, 2003). BP, Chevron/Texaco, Exxon/Mobil, Ford, and General Electric have also locked up the services of many of America's top energy scientists, devoting more than $270 million to hydrogen research at MIT, Princeton, and Stanford. Such funding will help ensure that oil and gas producers continue to profit even if automakers manage to put millions of fuel-cell cars on the road (Lynn, 2003). Along with the big automakers, energy companies also formed a consortium called the International Hydrogen Infrastructure Group to monitor federal officials charged with developing fuel cells. "Basically," says Neil Rossmeissl, a hydrogen standards expert at the Department of

[38] http://www.cafcp.org/index.html

Energy, " what they do is look over our shoulder at DOE to make sure we are doing what they think is the right thing" (Lynn, 2003). Apart from these partnerships and strategic moves, many other examples can be given, U.S. related, but also international.

Stimulated by the articulation of promises and expectations by the car and oil industries, soon other industries also got interested in hydrogen technologies and joined the NHA as well. Especially nuclear companies and to a lesser extent electricity utilities recognized their potential role in the new energy market. Today the NHA is the largest trade association for hydrogen in the world, according to Patrick Serfass, Director of Program and Technology Development. The NHA has over hundred members, including major industry, small business, government, and university organizations.[39] Each represents a stakeholder in some aspect of the developing hydrogen economy. With the growth of NHA, the interests and the program grew very quickly as well. The NHA's mission is to foster the development of hydrogen technologies and their utilization in industrial, commercial, and consumer applications and promote the role of hydrogen in the energy field. The NHA represents all of its members, but is still non-biased. The eventual goal of NHA, however, is to pursue hydrogen based on renewable energy sources. According to Debbi Smith, Executive Vice President of NHA, all NHA members are in favor of renewable energy sources. The companies quickly began to use the association as a platform to lobby for more federal funding for research and to push the government to emphasize certain technologies and sources in the national energy plan for hydrogen.[40] Today the NHA can be seen as a specific actor more than merely as a platform and is very actively involved in the hydrogen debate.

As stated before, apart from the oil industries, especially the nuclear industry began to realize that they can play an important role in a future hydrogen economy. Nuclear companies started to focus on new technological developments that would strengthen their position in the hydrogen transition. An example of such a technology is the synfuels production from carbon dioxide, developed by General Atomics, as discussed in section 4.3.1.3. Moreover, the industry started to articulate the promises and expectations about nuclear hydrogen: at the annual meeting of the World Nuclear Association in London September 2002, the group's director general, John Ritch, touted what he called the "hydrogen-nuclear economy." He envisions "an entirely clean energy global economy, with nuclear power supplying not only electricity and clean water, but also energizing transport of all kinds." In May 2002, General Atomics held a workshop on producing hydrogen from both conventional nuclear fission and as-yet unproven nuclear fusion. (Motavalli, 2003). The motivation for General Atomics to get involved in hydrogen technologies is, according to Kenneth Schultz, that it creates new business opportunities for them and by doing this they try to stimulate nuclear energy in politics.[41]

To sum up, after the articulation of promises and expectations about hydrogen by the oil industry, hydrogen gained momentum very fast, not only in industries as discussed above, but also in research institutes and universities. The articulation processes put hydrogen on the agenda of many actors and resulted in several strategic games. By

[39] A full list of members can be found on: http://www.hydrogenassociation.org/about/members.asp?sort=2
[40] Data from interview with Patrick Serfass and Debbi Smith, NHA
[41] Data from interview with Kenneth Schultz

forming or joining platforms and partnerships and by means of new articulation processes, as for example with the nuclear industry, the different actors try to position and prepare themselves for the hydrogen transition. This all had its effect in politics.

5.2.2 The Government

Stimulated by the industries and research institutes and by the landscape pressures described in chapter 4, fuel cell research and development gained a greater share of government funding and hydrogen became a more and more important issue on the political agenda. In January 2002 the Bush Administration introduced the FreedomCAR program. The FreedomCAR program is a cooperative research program between the Big 3 automobile manufacturers (Ford, GM, DaimlerChrysler), major energy companies (particularly oil companies), and the government to develop a new generation of vehicles, fuels, and the infrastructure necessary to support it (National Academies, 2005). The partners jointly conduct technology roadmapping, determine technical requirements, suggest R&D priorities, and monitor the R&D activities necessary to achieve the goals of the Partnership (EERE, 2005). Such programs are, however, not new. The last couple of decades has seen similar programs with limited success. It is not unthinkable that these programs are more or less just initiated to show that the government and industries are doing something.

On April 2-3, 2002, the U.S. Department of Energy (DOE) organized the National Hydrogen Energy Roadmap Workshop in Washington, DC. During the workshop more than 200 participants – representing hydrogen energy industries, academia, environmental organizations, federal and state government agencies, and National Laboratories – discussed the actions that need to be taken in order to reach the hydrogen economy. The intent was to identify the most important barriers and needs that should to be addressed in order to achieve the vision, the time frames for the top priority research and development and other efforts, and the respective roles of industry, government, universities, and National Laboratories in dealing with these issues (Energetics, 2002).

These and suchlike activities in politics eventually led to the announcement of the Hydrogen Initiative and the $1.2 billion budget in 2003. Figure 19 shows the breakdown of federal spending on hydrogen R&D for 2004. Money on R&D for hydrogen from natural gas, coal and nuclear accounted together for 9% of the more than $180 million (National Academies, 2004). The DOE's Office of Energy Efficiency & Renewable Energies (EERE) houses the majority of the programs (Production & Delivery; Storage; Infrastructure Validation; Safety, Codes & Standards, etc; Education & Analysis). Other DOE offices involved are Fossil Energy (Hydrogen from Gas, Hydrogen from Coal) and Nuclear Energy (Hydrogen from Nuclear) (Martin, 2005).

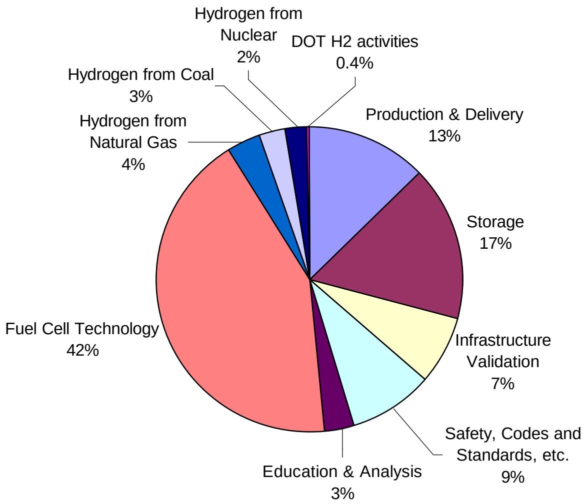

Figure 19: U.S. Spending on Hydrogen R&D in 2004 (National Academies, 2004)

According to the National Academies 2004 report, the DOE reports an additional $300 million spent on associated programs (National Academies, 2004). Associated programs are defined as those necessary for a hydrogen pathway, but which would probably occur even if there were no DOE hydrogen activities. An example would be R&D into carbon dioxide sequestration—a technology that is not necessary for hydrogen production but which would make hydrogen production from fossil fuels (currently the cheapest way to produce hydrogen) environmentally sound (Martin, 2005). The majority of the money in associated programs was spent on fossil fuel programs and on the President's FreedomCAR program. Other hydrogen programs the government is involved in are FutureGen and the Nuclear Hydrogen Initiative.

On February 27, 2003, President Bush announced that the United States would sponsor a $1 billion, 10-year demonstration project to create the world's first coal-based, zero-emissions electricity and hydrogen power plant: *FutureGen*. FutureGen is an initiative to build the world's first integrated sequestration and hydrogen production research power plant. When operational, the prototype will be the cleanest fossil fuel fired power plant in the world (DOE, 2003). The FutureGen Industrial Alliance, a non-profit consortium of some of the largest coal producers and users in the world, was formed to partner with the U.S. Department of Energy on the FutureGen project[42] and on December 6, 2005, Secretary of Energy Samuel W. Bodman announced that the DOE has signed an agreement with the FutureGen Industrial Alliance to build FutureGen (DOE, 2005). FutureGen Alliance members intend to contribute up to $250 million toward the project's costs and, in addition, will bring valuable technical expertise and industrial project management experience to the project. Further, the FutureGen Alliance will facilitate the introduction of advanced technologies into the plant that are based upon billions of dollars of past industrial investment.[43]

[42] FutureGen Industrial Alliance [Online] http://www.futuregenalliance.org/. See website for member companies
[43] Ibid

In addition to FutureGen, the *Nuclear Hydrogen Initiative* is an important research and demonstration program. During the National Hydrogen Energy Roadmap Workshop in 2002 representatives from the nuclear industry projected that, with funding from industry and the DOE, they could have a pilot plant for producing hydrogen from nuclear power in place by 2010 (Motavalli, 2003). As part of the Presidents Hydrogen Initiative, in 2003 the Nuclear Hydrogen Initiative was announced and in 2004 Nuclear Hydrogen received a budget of $6.2 million (DOE/NEST, 2004). The goal of the Nuclear Hydrogen Initiative is to demonstrate the economic commercial-scale production of hydrogen using nuclear energy by 2015, and thereby make available a large-scale, emission-free, domestic hydrogen production capability to fuel the approaching hydrogen economy (DOE/NEST, 2003). This project, which is part of a $1.3 billion project to construct a new experimental reactor, will apply the dual hydrogen and electricity production that will characterize FutureGen as well.

Governmental support for nuclear energy became once again clear in the President's budget for 2006, which was released early February. The budget showed an increase of over 200% in the funding for advanced nuclear fuel cycle R&D, as part of the Advanced Energy Initiative to help break America's dependence on foreign sources of energy.

Thus, the government, who is interested in alternative technologies that can be a solution for the concerns at the landscape level, as discussed in chapter 4, got attracted to hydrogen by articulation processes from industries, but also from research institutes and national labs. This led to the Hydrogen Initiative and its associated programs. By this focus on hydrogen it is now the government that constructs and communicates positive expectations and tries to attract attention and enroll more actors to widen the social network. This is what happened in, for example, the FutureGen project. The governments focus on hydrogen also (indirectly) stimulated the renewable industries to get involved as I will discuss now.

5.2.3 Renewable Industries

It was not until the National Hydrogen Energy Roadmap Workshop in 2002 that renewable industries started to interfere in the hydrogen debate significantly. The American Solar Energy Society (ASES)[44] took a leading role in promoting renewable hydrogen in 2002, when then-ASES Chair Mike Nicklas attended the Workshop. Nicklas was enraged by the small role he saw for renewables in the administration's hydrogen roadmap. He soon focused on the need for a forum gathering renewable energy experts and organizations to ensure that renewables play a significant role in the research for hydrogen-production sources. Thus, the Renewable Hydrogen Forum was born.[45] Ron Larson, as both a member of the ASES board and alumnus of the National Renewable Energy Laboratory (NREL), chaired the effort. The forum took place in April 2003 in Washington, D.C., and included presentations by dozens of renewable energy authorities.

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[44] ASES is a national organization dedicated to advancing the use of solar energy for the benefit of U.S. citizens and the global environment. ASES promotes the widespread near- and long-term use of solar energy. Apart from solar, ASES is dedicated to the development and adoption of renewable energy in all its forms.

[45] Information from interviews with Ron Larson, chair of ASES

The forum, attended by about 50 participants, emphasized the potential of renewable hydrogen, its benefits and needed development. Since the Renewable Hydrogen Forum, there has been an increasing industry concern surrounding the prospects for a renewable hydrogen energy economy[46] and today the NHA also has industry members that develop renewable hydrogen technologies, like Hydrogen Solar Ltd and Solar Integrated[47].

According to Ron Larson, who is the present Chair of ASES, "it was never the intention of the organizers of the forum to promote hydrogen; the intention was to make sure that if hydrogen goes on, then renewables are involved and to make sure that not all money goes away from renewables. This is still the position of the majority of the members." However, as the breakdown of federal spending on hydrogen R&D for 2004 shows (see figure 19), there is no budget for renewables. If money goes away from renewable programs to hydrogen programs is not totally clear, not to mention that it has been proven. However, it is clear that, based on information from the annual federal R&D funding reports from the National Science Foundation, the DOE R&D budget for the renewable energy program fell from $386 million in 1995 (2005 dollars) to $270 million in 2005. This is a decrease of 30 percent. The R&D budget for energy conservation increased from $450 million in 1995 (2005 dollars) to $518 million in 2001 (2005 dollars) and then fell back till $345 million in 2005, an overall decrease of 23 percent. During this time period, however, the total R&D budget for the Department of Energy decreased by 50 percent. Figure 20 shows all three budgets from 1995 till 2005. As a comparison: the budget for national defense rose by more than 50 percent in the same period. Moreover, on one estimate, America has spent some $60 billion a year during the 1990s to guard oil from the Persian Gulf, when the actual cash value of those oil imports totaled only around $10 billion a year – a mind-boggling subsidy for fossil fuel energy (Vaitheeswaran, 2003).

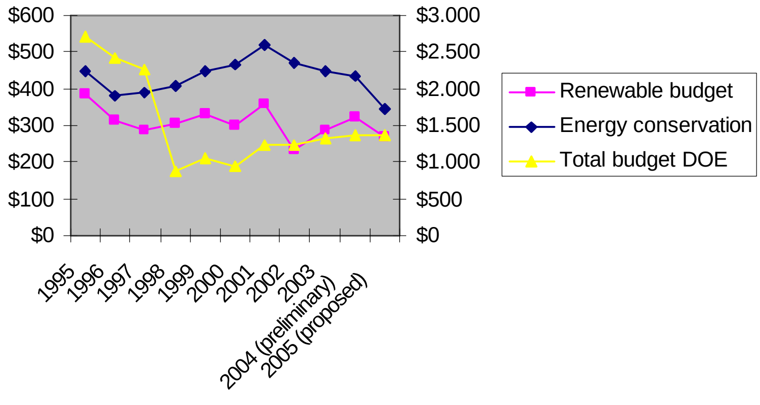

Figure 20: DOE's R&D spending (in millions 2005$) (Source: National Science Foundation)

To increase the influence of renewables in politics ASES joined the 25x'25 coalition. 25x'25 was formed by farmers and is a rallying cry for renewable energy and a goal for America – to get 25 percent of our energy from renewable resources like wind,

[46] Ibid
[47] http://www.hydrogenassociation.org/about/members.asp?sort=2

solar, and biofuels by the year 2025. A group of volunteer farm leaders first envisioned the goal of 25x'25, and it quickly gained the support of a broad cross-section of the agriculture and forestry communities. Now leaders from business, labor, conservation and religious groups are joining this alliance as well.[48] Across the country, farmers, ranchers, forest land owners and other leaders in the community are coming together in state-level alliances to explore how the 25x'25 vision can help accomplish state energy, environmental and rural development goals.[49] In 2004, ethanol production created 130,000 jobs across all economic sectors.[50]

According to Ron Larson from ASES, especially rural development and economic issues have the potential to influence politics. That is the reason why ASES joined the 25x’25 coalition. It is not peak-oil or environmental issues that mainly drive this coalition, but it is jobs and rural development. “This coalition is going to drive things. I believe in it. Bush seems to have no, or only small, interest in environmental issues, but he is sensitive for pressure from farmers, who mostly are Republicans.” In general Larson thinks that forming coalitions is the best way to form a block against the power of the big industries.[51]

Unlike the solar industry, only few activities related to hydrogen developments come from the wind industry. The largest purchaser of wind energy, Xcel Energy announced in October 2005 that they, together with the National Renewable Energy Laboratory (NREL) plan to use wind power to create hydrogen fuel in a $1.75 million pilot program (Fuel Cell Works, 2005). The idea is to increase the efficiency of wind generation by using it during off-peak hours to produce hydrogen. The hydrogen would be stored, then used later to produce electricity during periods of peak demand. The program is said to be one of the nation’s first attempts to combine the two energy resources wind and hydrogen and is expected to increase the efficiency of the hydrogen production by wind from 3 percent to 6 percent (Fuel Cell Works, 2005). Apart from this planned project, clear signals of hydrogen development in the wind industry are absent. According to Norie Flowers, Assistant to the Executive Director of the American Wind Energy Association (AWEA), most members of AWEA are indeed mainly focusing on wind energy generation itself and not on hydrogen.[52]

Thus, although the renewable industry itself seems not too interested in hydrogen production yet – mainly because of the fact that today it is better to use renewables for electricity production, as Romm (2004) and Flowers indicate – their concerns about the articulation processes of promises and expectations of other industries and its influence on federal funding raised. So, stimulated by these processes, the Renewable Hydrogen Forum was established and the renewable industry started to articulate their promises and expectations as well, in order to protect renewable funding.

[48] http://www.25x25.org/about_25x25.php
[49] http://www.25x25.org/in_the_states.php
[50] http://www.25x25.org/renewables_biofuels.php
[51] Information from interviews with Ron Larson, chair of ASES
[52] Data from interview with Norie Flowers, AWEA

5.2.4 Environmental organizations

With an increasing interest in the hydrogen economy among industries and governments, environmental organizations also started to interfere in the debate. Their goal, not surprisingly, is to influence the developments, and especially the government's funding and policies, so that the environment is favored mostly.

By increasing public awareness, but mainly by lobbying in politics, environmental organizations try to influence the government and the developments. Recent years have shown an increasing interest among environmental organizations in market-based approaches, away from technology-stimulating approaches. Environmental Defense was first among the major, national environmental organizations to advocate these incentive based policies. According to Bill Chameides, Chief Scientist at Environmental Defense, "politics should come up with legislation, and then let the market decide which technology will work best. The market will come up with solutions, as long as they receive the right signals from government. If hydrogen turns out to be the best solution, good. If not, then not." "We consider a cap and trade system as the best solution for the problem. A lot of states already have this legislation, with success. Now it is time that the federal government follows."[53] Thus, Environmental Defense is interested in reduction of emissions itself, regardless of which particular technology is the best solution.

Environmental Defense helped BP with cutting greenhouse gas emissions by turning to market forces. BP launched an innovative internal market for emissions trading among its many divisions around the world and, despite many doubts and skepticism, in 2002 the firm announced spectacular results: it had met its target for emissions reductions 7 years ahead of schedule. According to Lord Browne, the head of BP, the costs of tackling climate change are "clearly lower than many feared. This is a manageable problem" (Vaitheeswaran, 2003).

According to Vaitheeswaran (2003) the lesson for the world at large is clear. "If those at the top send an unambiguous signal that climate change is important, and if they encourage market-based solutions, industry will respond with a blunderbuss of innovation that produces the lowest cost solution to this thorniest of problems."

Where one would expect that environmental organizations would be in favor of renewable energy sources, this is apparently not necessarily true. The main goal is to reduce greenhouse gas emissions and thus hydrogen from natural gas or from goal can be the most favorable technology as long as it reduces overall emissions significantly. This strategy makes sense from a point of view that history has shown that large amounts of federal money have been wasted on technology-stimulating projects. The (development of the) Battery Electric Vehicle (BEV), a technology that seemed to be promising and was considered to be a solution for our environmental and petroleum problems, for example, was heavily stimulated, but soon after its introduction on the market the BEV disappeared more or less from the road and from the development agendas. Hybrid Electric Vehilces and Fuel Cell Electric Vehicles displaced the BEV programs and although these vehicles systems are based on BEVs, a lot of money has been spent on BEVs and its infrastructure without getting the expected return.

Although the market-stance from environmental organizations avoids governmental wasting of money on technology projects and might be a good solution for

[53] Data from interview with Bill Chameides, Environmental Defense

emission reduction, there are also negative issues related to market-based solutions. I will come back to this in chapter 7.

5.2.5 Users

Car manufacturers have a significant influence on the hydrogen transition in the transportation sector. Fuel cell vehicles are seen as a desirable and inevitable future. Apart from the, in section 4.3.4 mentioned, advantages of (PEM) fuel cells, additional attractions for automakers are the elimination of most mechanical and hydraulic subsystems. This provides greater design flexibility and allows more efficient manufacturing approaches (Sperling and Ogden, 2004). The technologies that car manufacturers will use eventually in their vehicles, the amount of vehicles they will produce at what time, and the success they will have with fuel cell technologies, have a strong influence on the hydrogen transition.

Car manufacturers are looking for a smooth transition towards a hydrogen economy. They have large investments in combustion engine vehicle technologies and will try to protect their sunk costs. This is one of the reasons why American car manufacturers oppose an increase in fuel economy standards and did not endorse hybrid vehicles; “they insist that they cannot meet higher standards without unacceptably big price hikes or massive investments in technology” (Vaitheeswaran, 2003). On the other hand, auto manufacturers see benefits from being first to market and if hydrogen vehicles turn out to be the technology of choice they can established themselves as world leaders in the technology. Hydrogen fuel cells are seen as the desirable next step and automakers are committed to move fuel cells from the lab to the marketplace. The key question is whether and when they will drive up current investments of perhaps $150 million per year to the much larger sums needed to tool factories and launch commercial products (Sperling and Ogden, 2004). Without automaker leadership, the transition will be slow, building on small entrepreneurial investments in niche opportunities, such as fuel cells in off-road industrial equipment, hydrogen blends in natural gas buses, innovative low-cost delivery of hydrogen to small users, and small energy stations simultaneously powering remote buildings and vehicle fleets (Sperling and Ogden, 2004). The way car manufacturers steer the transition is very important for hydrogen suppliers and results in the before mentioned ‘chicken-egg’ problem. Hydrogen suppliers are not likely to invest in an infrastructure when the amount of FCV is still small and car manufacturers foresee problems with bringing FCV on the market when a decent fueling infrastructure is absent.

Apart from ‘how many’ and ‘when’, the technologies used in FCV have a strong influence on the hydrogen transition. Car manufacturers have no good reason to value one hydrogen production method over another, except for the fact that the cheaper the hydrogen is, the more popular their future FCV would be. They do have good reasons, however, to value one storage method over another. All major car companies are focused on direct hydrogen FCVs, in which hydrogen is stored on-board. Today the main method of storage is hydrogen compressed gas. With new technologies the dominant method might change in the future and carbon nanotube ‘cartridges’, for example, might become the future storage method of choice. This directly influences the preferred production and especially distribution and storage systems. The in section 5.2.1 mentioned partnerships and groups between car manufacturers and fuel suppliers were formed to work on problems like this.

The role of fleet companies, end-users and non-users is still very small. Apart from a few demonstration and bus projects, hydrogen as a fuel is not commercial yet. Based on the image of users that developers have, however, costs, safety and, to a lesser extent, the possibility of refueling fast, are seen as key factors in public acceptance of hydrogen as a fuel, or more general of any fuel. A frugal consumer will not buy a hydrogen fuel cell vehicle if it, and the fuel, cost more than a conventional one (Tseng et al, 2005). Regarding safety, explosions and leaks are the main domain of this problem. Hydrogen is invariably associated with the spectacular Hindenburg accident (explosion of a zeppelin filled with hydrogen in 1937) and thought of as a dangerous substance by the general public. Hydrogen's success therefore, apart from technological or economic factors, also dependents upon the willingness of the general population to assume the actual and perceived risks and hazards associated with it (Utgikar and Thiesen, 2005).

Studies are carried out to discover the public's attitude towards hydrogen. The international project AcceptH2 aims to understand and measure public perception of hydrogen buses in different locations. This study shows that, although the positive associations regarding hydrogen are relatively small, European and Australian markets[54] supports the hydrogen transition (AcceptH2, 2004). However, surveys are not a true representation of reality. It is easy to say that you accept a technology when the technology is not there yet and the impacts are unknown. Public acceptance might change completely as soon as the hydrogen gets more diffused, a hydrogen pipeline is planned to be build near your house, or a serious hydrogen accident occurs. Rick Zalesky of Chevron/Texaco does not see problems with public acceptance regarding hydrogen's safety. "Oil is dangerous, maybe even more dangerous than hydrogen, but got accepted and it's been around for a long time now. People get used to it. By educating the people about hydrogen and by means of demonstration programs, people will accept hydrogen as well."[55]

It is hard to say if hydrogen will or will not encounter significant public resistance. Many technologies have failed because the public did not accept it for various reasons or preferred other technologies. Public resistance can thus have a serious influence on the transition and needs to be taken into account. This does not only relate to hydrogen itself, but also to new nuclear reactors, or even to carbon dioxide sequestration and storage.

Although the actions and interests of the big oil companies related to the hydrogen transition have been discussed above, there is a need to explore them a little further. From the beginning of this chapter it becomes clear that the oil industries had a key role in the articulation of promises and expectation, what led to increasing interest in the hydrogen transition. However, these industries dictate the current petroleum regime and have incentives to resist the pressure from the macro level (the landscape) and from the micro level (the niches) and to slow down the transition. I will now take a closer look at how the transition process is influenced by the existing regime.

[54] No data about the U.S. is available yet

[55] Data from interview with Rick Zalesky, Chevron/Texaco

5.2.6 Influence of Existing Regime

Although all different industries and companies have a shared interest in supplying the hydrogen for the future, the oil companies, as important actor in the existing petroleum regime, have a special position and have, in addition to an interest in future market share, an interest of a different kind: a slow and smooth transition. Albeit the petroleum regime contains many more actors than just oil companies like Shell, BP and Exxon, I will now take a closer look at how the transition process is influenced by these companies in particular.

Oil companies try, by actively participating in the hydrogen developments and by improving existing oil production methods, to create a most favorable transition for their own business. Major oil companies have invested hundreds of billions of dollars in their business. Therefore there is a real interest in keeping and utilizing that infrastructure in the future. To avoid possible sunk costs that will result from a quick transition to hydrogen there is an incentive to make a smooth transition, or even slow down the transition process. Moreover, while other industries might favor a quick transition so that they can enter their new transportation market in the near term, oil companies dictate the transportation market already, so there are no benefits for them to speed up the process. Although they invest a lot in, for example, renewables (especially Shell and BP), oil companies also invest a lot of money in new oil production methods like oil shale, tar sand, and deep gas technologies, and in the improvement of existing production and extraction methods. This is called the ‘sailing ship’ effect (Geels, 2002). By doing that, the oil companies try to slow down the hydrogen transition as much as possible.

According to Sperling and Ogden (2004), without government support during the low-volume transition stage, oil companies are also unlikely to be early investors in the construction of hydrogen infrastructure. They are best characterized as watchful, strategically positioning themselves to play a large role if and when hydrogen takes off. Because of their size and capital strength, as mentioned before, they can afford doing that. A common strategy is, for example, buying up small successful companies as soon as hydrogen takes off, or before in order to avoid their further success and thus decrease the pressure on the regime.

In addition to that, oil companies also try to influence and steer the developments by putting pressure on politics. For a better understanding of oil’s influence it is important to get a rough idea of the power of the oil industries in U.S. politics and to see why policies are strongly influenced by it. First of all, the size and capital strength of the industry is important. As mentioned before the oil industry is the biggest industry in the world, and oil companies are strongly presented in the top largest countries in the world and in the U.S. Moreover, this single industry controls almost all other industries, since oil or oil products are a driver for most industries. This means that the oil industry has a huge influence on the whole economy.

Secondly, American politics is not only strongly driven by votes, but by money as well. Billions of dollars are spent on campaigns, and big industries are the main supporters. Since 1990 the oil and gas industry has sponsored politicians with a total amount of money of almost $187 million, varying from $10.5 million in 1990 till $34.3 million in 2000, an increase of more than 200% in 10 years. In this top year 2000 Chevron/Texaco, Exxon and BP were among the four main contributors. The oil and gas industry belongs to the top 10 contributors to politics and the bulk of the money goes to

Republicans: 75% of the $187 million since 1990 (Center for Responsive Politics, 2006). Politicians, especially Republicans, thus have a strong incentive to develop policies that favor the oil and gas industry.

Third, oil companies employ many employees. The 6 largest oil companies in the world employ a total of almost 400,000 employees worldwide (Global 500, 2005) and for states like Texas, the oil industry is important for employment. Policies that do not favor these companies might cause serious impacts in employment in areas like Texas, which can again influence economies. Moreover, policies that favor the oil companies and their labor unions will result in many votes during elections.

Thus, although the oil industry is heavily involved in the hydrogen transition, at the same time they try to slow down the transition process in order to protect their existing businesses. This happens at all three levels of the transition process. By improving existing oil production technologies and developing new production methods, the position of the petroleum regime is tried to strengthen again and the internal pressures of peak-oil and foreign energy are tried to solve. At the landscape level, oil companies strongly influence politics by putting pressure on it. That way they try to avoid legislation that will harm them. At the micro-level, oil companies buy up small successful companies to avoid their further success and thus decrease the pressure on the regime.

Now that the interests, actions, and views of the most important actors are explored, I will analyze the role of a technological nexus in the development process.

5.2.7 Co-evolution

As mentioned in the previous chapter, apart from anticipation, a technological nexus also plays an important role in variation and selection processes. As stated in section 2.1, the technological nexus role implies considering both the selection and variation process as a resource and an option: that is, activities that can and must be molded and harmonized through active efforts. In most cases the nexus is specific, describing the relation between technological variation and environmental selection.

A technological nexus functions as the link between developers and users. These nexuses are clearly visible in the hydrogen developments. The partnerships mentioned before between future hydrogen suppliers, especially the oil industries, and the car manufacturers as being users of hydrogen are examples of a technological nexus. The California Fuel Cell Partnership, the International Hydrogen Infrastructure Group and the FreedomCAR partnership were all formed to work together towards the hydrogen transition and to learn from each other. Apart from car manufacturers and oil companies, the government, or governmental agencies, are involved as well in California Fuel Cell Partnership and the FreedomCAR partnership. The government, the developers and the users all articulate their interest, technologies, policy, etc. In partnerships like these, the variation and selection processes discussed in chapter 4 are brought together. The 2002 Workshop from DOE is another example of where that happened.

As said before the role of end-users is still very small. In general market or environmental departments of companies fulfill the nexus role between the developer and the end-user. This is clearly visible within car companies where institutional links are formed within the (bus) demonstration projects and with the test drivers of fuel cell cars. Regarding the hydrogen itself these links between the hydrogen developer and the end-user do, however, not really exist in the way they do with car manufacturers. AcceptH2 can be seen as a technological nexus, although this project was not initiated or funded by hydrogen suppliers, but by governments. Governments, however, also fulfill the role of developer, since they are heavily involved in hydrogen research projects and by creating this link with the end-user they tried to get a better understanding of the public's perspective and acceptance of hydrogen technologies. The objective of the project is to assess economic preferences towards the potential and actual use of hydrogen buses. This is an important aspect not only for governments, but also for hydrogen suppliers.

Apart from the institutional links with users, technological nexuses exist between developers and governments, either in joint projects or in extensive contacts and lobby processes. FutureGen and the Nuclear Hydrogen Initiative are examples of this. Coal and nuclear companies (variation) work together with the government (both variation and selection) on pilot projects that serve as an example for the future hydrogen economy. Finally, links exist between developers and environmental organizations and between governments and environmental organizations. These contacts are mostly characterized by their ad hoc nature and are in general initiated by the environmental organizations. Articulation of societal and political questions and problems are the main goal of these links, more than articulation of demand or technical specifications.

5.3 Conclusion

Although fuel cells and hydrogen as a fuel were seen as promising long time ago already, and research institutes, scientists and small companies expressed this, it was not before the late 1990s that automotive and oil companies started to articulate promises and raise expectations about the technology. Expectations and promises were now shared among the two most influential industries in the transportation sector and the articulation of expectations created a prospective structure. Although this does not mean that the car and oil industries fully committed themselves to FCVs and hydrogen, these stories and structures created new patterns and institutions and the promising technologies were taken up in the industries' agendas. The oil and car industries started to join and form groups and partnerships and even established subsidiary companies. Stimulated by the articulation of promises and expectations by the car and oil industries, soon other energy industries, especially the nuclear industry, got interested in hydrogen technologies and started to articulate their own promising technologies and expectations. These processes caused a rise in interest in politics as well and led to the Hydrogen Initiative and its $1.2 billion budget and associated programs like FutureGen and the Nuclear Hydrogen Initiative.

The articulation of promises and expectations play a very important role in technological change. The prospective structures that are created are forceful due to the perceived implications of the projected future. These articulation processes therefore cause a significant pressure on the existing regime and are an important strategic move for new actors. These parties construct and communicate positive expectations in order to make other actors believe that it will yield returns in future and to get support. The prospective structures therefore do not only have an impact on the agenda of the actor that creates them, but also on the agenda of the actors that pick up the structures and start to believe in the promises and technologies. This is what can be seen in the federal funding of hydrogen projects. Based on the promises and expectations, and the articulation of it by actors – not only actors from the big powerful industries, but also scientists from the government for example – the government and DOE allocate the budgets. Very promising technologies, which are expected to yield returns in future, are more likely to receive money than technologies of which the future profit is more uncertain are. The importance of articulating promises and expectations was recognized by renewable actors as well, especially by the American Solar Energy Society (ASES). Although members of ASES do not even particularly support a hydrogen transition, they articulated their own promises and expectations in order to protect their federal budgets. Thus, articulation processes are crucial for actors in order to play a role in the hydrogen transition and have an influence on the selection environment.

Among environmental organizations a trend is visible away from technology-stimulating approaches as described above. According to them it is much more important that the government sends the right signals to the market by means of legislation like a carbon cap and trade system. The market will come up with a solution and the government will not have to waste money on technologies that turn out to be not as promising as was expected and articulated initially. History has shown many examples in which the government, and companies as well, bet on the wrong 'promising' technologies and wasted large amount of money on it, without getting the expected profits. Therefore governments should focus on market-approaches instead, according to many environmental organizations.

Apart from articulating promises and expectations, forming partnership, and establishing subsidiary companies, other social mechanisms can be distinguished related to the hydrogen transition. Environmental organizations' efforts to increasing public awareness and to convince politics of the importance of market-based approaches, and the forming of coalitions like 25x'25, are examples of this. Moreover, social mechanisms play a role in the actions of the existing regime to slow down the transition. This happens at all three levels of the transition process. By improving existing oil production technologies and developing new production methods, the position of the petroleum regime is tried to strengthen again and the internal pressures of peak-oil and foreign energy are tried to solve. At the landscape level, oil companies strongly influence politics by putting pressure on it. That way they try to avoid legislation that will harm them. This power in politics is, like the articulation of promises and expectations a very important aspect of technological change. At the micro-level, oil companies buy up small successful companies to avoid their further success and thus decrease the pressure on the regime. Because of their size, economic importance and capital strength the influence of the actors in the existing petroleum regime on the transition process is very strong. The transition to clean energy will not happen overnight and the oil industry is unlikely to fade from the scene anytime soon.

In addition to the anticipation processes from chapter 4, technological nexuses play a role in variation and selection processes related to hydrogen technologies. Institutional links between hydrogen developers – especially oil companies – car manufacturers as hydrogen users, and the government as regulator and developer are formed to actively link the variation and environmental selection processes. The California Fuel Cell Partnership, the International Hydrogen Infrastructure Group and the FreedomCAR partnership are examples of where the different actors all articulate their interest, technologies, policy, etc. Technological nexus between hydrogen suppliers and end-users do not really exist. AcceptH2, a project that assesses economic preferences towards the potential and actual use of hydrogen buses, can be as a technological nexus, although this project was not initiated or funded by hydrogen suppliers, but by governments. This is an important aspect not only for governments that also function as hydrogen developers, but also for hydrogen suppliers. Apart from the institutional links with users, technological nexuses also exist between developers, governments, and other groups like environmental organizations, either in joint projects or in extensive contacts and lobby processes. FutureGen and the Nuclear Hydrogen Initiative are examples of that.

The position of car manufacturers as users of hydrogen technology and their actions have a direct important influence on the hydrogen transition. End-users, however, are still more or less out of sight. They do have an indirect influence though, by means of the image developers have of the prospective user. Especially cost and safety are seen as crucial aspects when it comes to public acceptance.

In the next chapter I will, based on this chapter and chapter 4, analyze the impacts that are likely to come with the production paths that are most aggressively pursued by industries and the government. These impacts will be assessed from the actors' point of view in a normative way.

6. Assessment of Impacts

The use of hydrogen as a fuel for our future economy will have several impacts on our society. Understanding of future impacts of new technologies is very limited though; many impacts only become visible during use and when the technology is applied on a large scale. The environmental problems that came with the existing transportation regime, for example, were not foreseen during the development of the technology and only came with massive use of automobiles. Despite the limited understanding, it is important to get an insight in the possible impacts in order to steer the developments in the right direction and avoid negative consequences.

In the first part of this chapter I will describe the most significant, likely impacts specifically related to the production paths that most likely will dominate the hydrogen economy for several decades: fossil and nuclear hydrogen (see Chapter 4 and 5). These impacts will be perceived and assessed differently by the different involved actors as we will see in the second part of this chapter. In this part the opinions of the actors about the desirability of the several impacts will be analyzed. Moreover, if normative principles play a role in the assessment, they will be analyzed as well.

6.1 Impact Analysis

There are many possible impacts related to fossil and nuclear hydrogen production method, of which the most significant and likely one will be described in this section. These impacts can be divided into direct and indirect impacts. Direct impacts are impacts that are intended to come with the technology and impacts mostly have an inevitable nature. Indirect impacts, or higher-order impacts, are initially unintended possible social or environmental changes that result from the use of the technology. If these indirect impacts will occur, depends on several factors and not only on the technology. An understanding of indirect impacts is important for a TA since they are, unlike direct impacts, mostly not intended. Moreover, by anticipating on the potential negative impacts during the process of technological developments, the developments can often be steered in such a way that negative impacts are avoided and positive impacts are stimulated (Smit and Oost, 1999). Most of the impacts described in this chapter are indirect impacts.
Section 6.1.1 describes the impacts related to centralized hydrogen production, section 6.1.2 the environmental impacts, and section 6.1.3 the establishment of GECF, the new gas OPEC. The impacts described in this chapter do not form an exhaustive list; other impacts can be thought of. Moreover, the impacts are specifically related to the prospective fossil and nuclear pathways. This means that impacts that are related to the hydrogen economy in general (e.g. efficient transportation technologies, safety issues, potential impacts on the three problems that characterize the landscape level) are left out of the analysis. I will also not discuss the impacts of nuclear energy itself in detail.

6.1.1 Centralized Production

As became clear from the previous chapters, in the U.S. it seems that the developments of the hydrogen production and distribution infrastructure are directed towards fossil fuel and nuclear based hydrogen production, at least for the coming decades. For the near term, hydrogen production from natural gas is expected to be the primary source, since this is the most cost-effective way to produce it. When demand increases, however, coal and nuclear plants are, in addition to natural gas, considered to be the best solution. This ‘best solution’ is not only stimulated by the big energy industries, but also by the government, as became clear from the previous chapters.

One of the direct effects of these production methods is that, because of their script, centralized production plants are required. Thus, our future energy system is likely to be based, again, on complex, large-scale, centralized, high-technology systems to produce energy. This will, or can, have several impacts on our society.

First of all, one of the direct impacts of a centralized hydrogen system is that an extensive distribution system is needed. As became clear from chapter 4, this system will most likely be a pipeline system. This problem regarding distribution has been discussed widely, both in literature and in the hydrogen debates. There is no unanimity among scientists and engineers about the possibilities of using the existing infrastructure. Where some claim that an entire new infrastructure needs to be built, others say that the natural gas pipelines can be used first, even in combination with natural gas, and later the infrastructure can be expanded if necessary. Building an entire new infrastructure will have an enormous impact on our society and will probably cause a lot of opposition.

Second, centralized hydrogen production can contribute to the creation of an oligopolistic regime structure again. An oligopoly is a market condition in which only a few sellers control the market and the actions of any one of the actors will affect price and competitors. The petroleum regime is characterized by an oligopolistic structure and as it looks right now, most likely only a few players will dictate the future energy supply again. This will make our future energy system vulnerable for limited competition and influential regime actors. Large corporate businesses, which came with the fossil fuel era, will continue to exist and will keep their power. Hydrogen has the potential to break down the regime and avoid the creation of a new oligopolistic regime structure. This can have many positive impacts on our society.

Third, focusing on centralized, complex, large-scale and costly systems can cause an indirect “lock-in” effect, as discussed in chapter 2 and 4. As Keith and Farell (2003) state it: “If we were certain that hydrogen fuel was the only long run solution to eliminating carbon dioxide emissions from cars, then it might make sense to focus R&D now, even though widespread deployment is decades away. If, however, we accept that there is considerable uncertainty about the optimum long run solution, then early commitment to hydrogen fuel is unwise because it risks technological lock in.” This is not only the case for hydrogen versus other fuels, but also relates to the uncertainty of the best solution for a future hydrogen production path. Socially and environmentally undesirable trajectories can be locked in through technological, institutional, and financial decisions made now that constrain future choices. By encouraging big nukes and big coal, the U.S. would be locking in all, dirty, inflexible, costly, and inefficient technologies for decades to come.

Forth, centralized energy systems can limit our personal freedom, another indirect impact. Like Lovins (1976) indicated with regard to our electrical world, in a centralized hydrogen economy, your lifeline does not come from an understandable neighborhood technology run by people you know who are at your own social level, but rather from an alien, remote, and perhaps humiliatingly uncontrollable technology run by a faraway, bureaucratized, technical elite who have probably never heard of you. Decisions about who shall have how much energy at what price also becomes centralized – a politically dangerous trend because it divides those who use energy from those who supply and regulate it (Lovins, 1976). The energy company serves the interests of big business rather than the interests of the public. This system will deprive the public of the freedom of a healthy environment, community control and ethnic identity. Moreover, people are dependent on big businesses. Today's energy system has these characteristics as well and limits our personal freedom, so in fact not much will change. Hydrogen, however, has the potential to increase our personal freedom as will be discussed in section 6.2.5.

Finally, centralized energy systems are vulnerable and risky. The scale and complexity of centralized grids increase the likelihood and size of malfunctions, the stakes and deliberate disruptions. A small fault or a few discontent people become able to turn off the country (Lovins, 1976). Moreover, large complex centralized systems are more vulnerable for sabotage and attacks, either from angry locals or terrorists. This has become a major performance criterion for any infrastructure system. Because of the initial high costs of centralized systems, and the uncertainties related to the hydrogen economy, the associated economic risks to capital in case of error, or in case of the appearance of different technologies and standards over time, are high as well.

To sum up, five impacts related to centralized hydrogen production, which comes with a focus on fossil and nuclear sources, have been distinguished. These are the need for an extensive distribution network, the risk of creating an oligopolistic fuel regime again, the risk of locking-in complex technologies, the negative impact on our personal freedom, and the creation of a vulnerable and risky energy system.

6.1.2 Environment and Sustainability

Fuel cell vehicles are the least polluting of all vehicles that consume fuel directly. Fuel cell vehicles operating on hydrogen stored on-board produce zero pollution (at the tail) in the conventional sense. Neither conventional pollutants nor greenhouse gases are emitted. The only byproducts are water and heat and therefore fuel cells have a direct positive impact on the environment. However, although the emission of a fuel cell vehicle with on-board storage is zero at the tail, hydrogen use as a fuel is not totally benign from an environmental standpoint. Since hydrogen is an energy carrier and not an energy source, an additional source of energy is needed to produce hydrogen, as has been discussed extensively in Chapter 4. The choice for this additional source of energy has a great influence on the overall pollution of FCVs.

Fossil fuels are the main source of energy for the production of hydrogen and are expected to maintain that position the coming decades. Any conversion of a carbonaceous fossil fuel to a fuel of lower carbon content – including the conversion all the way to hydrogen – will eject the excess carbon as carbon dioxide. The problem of its emission to the atmosphere is simply transferred from the points of consumption (the tailpipe) to the location where the conversion process takes place (Weisz, 2004). For a sound comparison of different alternatives, well-to-wheel analyses are therefore important. From such analyses, it seems that the combination of production and end-use is generally more acceptable for hydrogen than for alternative fuels. Extracting any fuel takes energy – even getting gasoline from well to pump costs the equivalent of 20% of the energy of the gasoline. It takes more energy to generate hydrogen than gasoline, but since a fuel cell is more efficient than conventional energy devices, fuel cell vehicles – even today's prototypes – offer attractive overall benefits, even using hydrogen (Edeskuty et al, 1979; Wang, 2002).

Some scientists are less positive about the environmental advantages of hydrogen. Romm (2004b) states that "a major effort to introduce hydrogen cars before 2030 would actually undermine efforts to reduce emissions of heat trapping greenhouse gases such as carbon dioxide." "Fueling a significant fraction of U.S. cars with hydrogen made from natural gas makes little sense, either economically or environmentally. From an environmental point of view it is much better to use the natural gas, apart from a few pilot projects with hydrogen, for the generation of electricity" (Romm, 2004b). For example, the well to wheels efficiency of a hydrogen car running on gas derived hydrogen is likely to be under 30 percent for the next two decades. The efficiency of gas-fired power plants is already 55 percent (and likely to be 60 percent or higher in 2020). Cogeneration of electricity and heat using natural gas is more than 80 percent efficient. And by displacing goal, the natural gas would be displacing a fuel that has much higher carbon emissions per unit of energy than gasoline. Romm (2004a) concludes that for these reasons, natural gas is far more cost effectively used to reduce CO2 emissions in electric generation than it is in transportation. Proponents of using natural gas claim, however, that the percentage of natural gas that will be used as a transition source will be so small that the influence on electricity generation is not worth mentioning.

Apart from natural gas, there is a huge environmental concern related to coal and nuclear hydrogen. Hydrogen production from coal emits a large amount of carbon dioxide, and although this might be sequestered and stored underground, the environmental risks are great. The practical use of the carbon capture and storage (CCS) technology is not proven yet and there is a risk that the stored carbon dioxide will be released to the atmosphere over time, because of failures, leakages, etc. It can cause serious problems in the future and therefore hydrogen from coal might not be the best solution for reducing carbon dioxide emissions. Regarding nuclear hydrogen similar risks and concerns are pointed out. Nuclear waste and possible accidents with disastrous consequences are seen as a serious risk for our environment and society.

The use of fossil and nuclear fuels for hydrogen production is not a sustainable solution as well. Fossil and nuclear fuels are not endless and the reserves are used up very fast. As discussed in Chapter 4, natural gas is expected to peak in about 2 decades from now. Coal reserves, both worldwide and in the U.S., are still very large and if demand remains frozen at the current rate of consumption, the U.S. coal reserves will last roughly 250 years. However, according to Weisz (2004), population and economic growth alone reduces the calculated lifetime to some 90-120 years. Any new uses of coal, like coal gasification for hydrogen production, would quickly reduce the lifetime of the U.S. coal base to less than 75 years (Weisz, 2004). Nuclear offers more perspective with new technologies. "Were the current nuclear technology expanded to provide electricity now supplied by coal (about 23 quads), the estimated U.S. uranium resources would be exhausted in about 35-58 years. However, advanced fission technologies that involve breeder methodologies and the use of thorium could expand that timeline to many hundreds of years" (Weisz, 2004). Apart from the reserves, nuclear waste has a negative impact on sustainability as well. If we do go on burning up the planet's legacy, the result may be irreversible damage to our climate and to future generations. The future therefore requires sustainable alternatives.

Thus, the carbon dioxide problem is not eliminated by a hydrogen economy if the chosen hydrogen path is continued to be followed. Nuclear hydrogen does not emit carbon dioxide, but it has its own environmental risks and problems. Moreover, apart from nuclear, the path set by the current energy policy and actions of the United States and the involved industries does not seem to be a sustainable path; solar derived and wind could be the major resources for sustainable hydrogen production for the U.S. The direct potential positive impact from hydrogen on the environment will thus be undermined by the indirect negative impacts of the chosen path. This path might not be the best solution for the environmental concerns at the landscape level.

In addition to environmental impacts of the specific path, environmental concerns and impacts related to the Hydrogen Initiative itself have been addressed as well. It has been said in the previous chapter that critics suggest that the Hydrogen Initiative is a tactical move to avoid policies such as strict fuel efficiency standards that could be readily implemented today. General Motors indeed said that the promise of hydrogen cars justified delaying fuel-efficiency regulations. Since hydrogen will not be a solution for environmental problems like air quality and global warming in the near term, focusing on it too much therefore undermines near term efforts. In line with that, the fact that the government is focusing on centralized fossil fuel and nuclear based hydrogen production, seems to derive the governmental attention away from renewable energy sources, as we have seen in the previous chapter, and thus creates a *non equal playing field*, which makes the market position of renewables, which already encounters many troubles, even more vulnerable.

6.1.3 GECF: The New 'Gas OPEC'?

If natural gas is used to produce hydrogen and if natural gas is imported, there would be little if any reduction in total energy imports, because natural gas for hydrogen would displace petroleum for gasoline. This can have an impact on the geopolitical situation and new power relations might arise.

Russia, a country with 28% of global natural gas reserves is aware of the increasing demand of, and dependence on, natural gas in the U.S. and other countries. They are preparing to take the leading position for guaranteeing the gas stability in the whole world, like Saudi Arabia has in the world of oil (Pravda, 2004). According to Agoulnik (2004), over the past several years, "the Kremlin has emerged, virtually unchallenged, as the dominant global player in natural gas already and Russia has even begun to organize the world's natural gas exporters under its aegis"; in 2001 the Gas Exporting Countries Forum (GECF) was founded.

The GECF is an informally structured group of some of the world's leading gas producers aimed at representing and promoting their mutual interests. Membership has fluctuated since the GECF's formation in 2001 but currently the GECF collectively controls 73% of the world's gas reserves and 41% of production. This collective strength has led to concerns by gas importers that the GECF has the potential to evolve into a gas version of OPEC (Datamonitor, 2005).

There are several factors that make it unlikely that GECF will emerge as the gas equivalent to OPEC (EBR, 2005): the diversity of interests and motivations of the different members; the existence of long term contracts in the gas industry; the fact that gas is not a global market; difficulties in allocating production quotas; and the threat of international anti-cartel laws (see EBR (2005) for further explanation). Despite its dominance of the world gas markets through its reserve and production levels, the GECF seems to be far from being a dominant or influential force in gas pricing.

However, natural gas meets one key requirement for price-fixing: a high degree of market concentration. In the last quarter of 2004 members of the forum accounted for 53% of the natural gas imported by the industrialized nations belonging to the Organization for Economic Cooperation & Development. That is in line with the 52% share of OECD oil imports that OPEC provided in that quarter, according to the International Energy Agency (Coy and Bush, 2005) and according to Coy and Bush the signs that natural gas producers are moving toward forming their own version of OPEC are troubling.

Russia has been boldest about trying to affect gas prices. As far back as 2002, Ronald Soligo and Amy Jaffe from Rice University say, it led the way in trying to get the forum to block European buyers from reselling their gas. “A resale ban makes it easier for producers to divide up the market and keep prices high. It is a favorite tactic of Saudi Arabia in the oil market” (Coy and Bush, 2005). Last year the Russian newspaper Izvestia quoted the deputy chairman of Gazprom, Alexander N. Ryazanov, as saying: “I think that it is in our countries’ interests to sell gas at the highest price possible. That is why one has to stick to correct approaches and coordinated policy” (Agoulnik, 2004; Pravda, 2004; Coy and Bush, 2005).

Thus, while not an immediate threat, the forming of the GECF cartel could have a serious impact on the geopolitical situation. Eventually a cartel will drive up prices for an essential element of the U.S. long-term energy supply and the dependence on foreign natural gas has the potential to change the political relationships with the exporting countries. It is not unlikely that Russia’s proven ability to dictate policy to Europe and the United States will result in new political tensions worldwide and will cause a movement of worldwide power relations. The potential positive impact of hydrogen on the geopolitical concerns at the landscape level is therefore undermined with the use of natural gas. This direct impact on the landscape level, and the creation of a natural gas OPEC need to be avoided.

Summarizing, the important impacts of the current hydrogen development direction discussed in this section are:

- Centralized
    - Distribution Network
    - Oligopolistic Regime Structure
    - Lock-in
    - Limiting Personal Freedom
    - Vulnerable and Risky

- Environmental Risks/ Sustainability
  Non equal playing field
- GECF: gas OPEC

I will now continue with a normative assessment of five of these impacts.

6.2 Normative Assessment of Impacts

In this second part of this chapter normative assessments of the possible impacts from the perspective of involved actors will be analyzed and evaluated. The opinions of the actors about the desirability of the several impacts will be analyzed. Moreover, if normative principles play a role in the assessment, they will be analyzed as well.

From the above indicated impacts five are interesting form the point of view of Technology Assessment. First, the impacts of the expected path towards hydrogen transition on the 'environment and sustainability' are an interesting problem for further analysis. Regarding these impacts the interests of the involved actors run straight into each other. Environmental interests usually experience a strong competition from economic interests. Moreover, ethical principles like our responsibility to take care of our environment and to create a sustainable livable world for future generations play a role.

The, to environment and sustainability related, 'non equal playing field' forms an interesting aspect for a TA as well. The non equal playing field creates an advantage for large fossil and nuclear industries, but at the same time a huge disadvantage for (small) renewable companies. There is thus a conflict in the assessment of this impact. Moreover, the 'right' use of public money is an interesting aspect in this.

Finally, the, to centralized production related impacts, 'distribution network', 'oligopolistic regime structure', and 'freedom' are interesting aspects for further analysis for a TA. The interests of the involved actors are, once again, contrary to each other. Moreover, the higher order impacts 'oligopolistic regime structure' and 'freedom' may lead to undesirable situations for involved actors, but are normally not foreseen during the development stage. Especially for 'freedom' ethical principles play an important role.

6.2.1 Environment and Sustainability

The undesirable environmental impacts and risks of the followed hydrogen path are, in fact, for all actors the same. For environmental organizations this will, however, be a greater concern than for the market parties that are in general more concerned about profits.[56] Although environmentalists in general favor renewables, most of them do admit that short-term fossil fuel solutions will be needed to make the transition. Typically environmentalists are not completely dismissive towards new technologies like carbon capture and storage (CCS) – they generally state that benefit is to be obtained from research in these areas – but they question both the amount and the way in which public money is being spent. Their three main points of critique are 1) that too much money is spent on hydrogen from fossil and nuclear energy, 2) that money is shifted away from efficiency and renewable energy research toward hydrogen and 3) that hydrogen will not have a positive impact on the environment in the near term, but only in the far future.

[56] Market parties do usually also take into account their 'green image' though.

Regarding the first point of critique, today's federal hydrogen budget indeed shows that there is no budget specifically for renewables, see figure 19 in section 5.2.2. The three budgets for hydrogen production are for natural gas, coal and nuclear. According to environmentalist Jim Motavalli (2003), DOE's hydrogen production scenario is bizarrely tilted toward nuclear power, echoing 2001 National Energy Policy. The policy directs the Secretary of Energy to vastly expand the nation's nuclear generating capacity, and to "develop next generation technology including hydrogen and fusion." Moreover, in a 'pro-nuke' paper prepared by DOE energy scientist Samuel Rosenbloom, renewable hydrogen production is described as "high risk" and "long term." (Rosenbloom, 2002; Motavalli, 2003). According to Motavalli fusion reactor developments show the same characteristics: despite hundreds of millions of dollars in funding over the past 50 years no practical process for a fusion reactor has yet been demonstrated.

The second point of critique is less obvious. The relation between budgets for the hydrogen program and other programs is not totally clear, not to mention that it has been proven. As shown in chapter 5, DOE's spending did, however, see a significant decline in money spent on renewables and energy efficiency. In section 6.2.2 I will come back to this.

Finally, hydrogen is indeed not expected to have a positive impact on the environment in the near term. The core concern, as Romm (2004b) argues is that, "a major effort to introduce hydrogen cars before 2030 would actually undermine efforts to reduce emissions of heat-trapping greenhouse gases such as CO_2." Many scientists and environmentalists, although they consider hydrogen a good solution for the future, share the opinion that there are much better off the shelf technologies today that can help us reduce CO_2 emissions on the short term. Pacala and Socolow (2004), for example, describe in their well-known article 'Stabilization Wedges' how the climate problem for the next 50 years can be solved with current, proven, off the shelf technologies. Among these technologies are efficient vehicles, buildings, and coal plants, reduced use of vehicles, nuclear, wind, and solar power, biomass fuels. According to Pacala and Socolow, in confronting the problem of greenhouse warming, the choice today is between action and delay. The hydrogen transition only has a positive effect in the far future and thus can be seen as delay. The National Resources Defense Council, an environmental action organization that tries to protect the planet's wildlife and wild places and to ensure a safe and healthy environment for all living things[57], agrees with that and in a policy paper they state that "[h]ydrogen fuels have long-term promise, but we need to act now to relieve dependence on foreign oil and reduce global warming pollution" (NRDC, 2004).

For politicians there is an interaction between environmental and economic aspects. In politics economic aspects mostly have the upper hand at the expense of environmental aspects. As has become clear from previous chapters, when it comes to the hydrogen transition the Bush administration seems to be more concerned about the economic and energy independence aspects than the environmental. Moreover, the economic importance of the big energy industries have, together with their power in politics, a significant influence on policies and it is not unusual that these industries, like the car industries, are favored or protected by policies, one way or the other. However, changes in this attitude are visible as well. Where in the late 1970's, when car companies

[57] http://www.nrdc.org/about/

were considered too big and too important to fail, Washington put up trade barriers to Japanese cars and trucks, and agreed to bail out Chrysler with government-backed loans aimed at preserving the company and its jobs, today, according to the New York Times of April 14, 2006, "the government shows no signs of hurrying to the rescue of General Motors and Ford that both flirt with bankruptcy" (Porter, 2006). In addition with that, a (rhetoric) trend towards more environmental concern and 'sustainability' is visible in political campaigns and debates. A poll conducted by Pew Research and released in April 2006, concluded that huge majorities of both political parties favor renewables – and more Republicans than Democrats support 'more research and deployment' on renewables at 82 percent compared to 77 percent (Sklar, 2006). Despite these trends, the government's chosen hydrogen path seems not to be the most environmental one.

The public, as well, becomes more aware of the importance of a sustainable society, although this is very relative. As soon as people have to pay for it, the concerns decrease a lot. People are inclined to prefer (their own) economy over a healthy environment, even though exposure to ozone, particulate, or airborne toxic chemicals has substantial health consequences.[58] Thus, related to self-interest, there seems to be a trade-off between a healthy environment and financial prosperity.

Americans are still overwhelmingly opposed to a higher federal gasoline tax, but the results of a New York Times/CBS News poll from February 2006 suggested Americans might accept a gasoline tax hike if it reduced global warming or lessened U.S. dependence on foreign oil. The Times said 85 percent of the 1,018 adults polled opposed a federal gas tax hike, but 55 percent said they would support such an increase if it did in fact reduce the U.S. dependence on foreign oil. And 59 percent were in favor if the result was less gasoline consumption and less global warming (Uchitelle and Thee, 2006).

Clearly, there is a trade-off between economy and environment. Apart from environmentalists, economic interests usually have the upper hand in actors' actions and decisions. This does not only relate to hydrogen technologies or the petroleum regime, but can be considered as a general aspect in our society. Moreover, this trade-off is a cultural one. The balance between the two interests differs from group to group and country to country. The Bush administration is known for its strong preference for economic and political interests and not environmental. As we will see in chapter 7, environmental concerns among the U.S. population are also low in comparison with other western countries.

From an ethical point of view, the interesting issue here is our responsibility in relation to the environment and sustainability. Before I will give an assessment related to the sustainability of the current development direction, I will first briefly discuss the concept 'sustainability'.

In 1987, the World Commission on Environment and Development (WCED), which had been set up in 1983, published a report entitled "Our common future". The document came to be known as the "Brundtland Report" after the Commission's chairwoman, Gro Harlem Brundtland. It developed guiding principles for sustainable development as it is generally understood today. The Brundtland Commission defined sustainability as "meeting the needs of the present generation without compromising the ability of future generations to meet their needs" (Brundtland, 1987). The underlying

[58] Polluted urban air is considered as a comparable health threat to passive smoking (http://www.fuelcells.org/basics/benefits.html)

notion is that current activities should not impoverish the future. In the most simple-minded way, sustainability might be taken to mean that the current generation should not use any non-renewable resources or rich ores since burning a gallon of gasoline today means that gasoline will be unavailable to future generations. Similarly, mining a rich ore body today means that future generations will be able to mine only leaner ore bodies. In line with that, anything done to deplete the soil, such as erosion is unsustainable (MacLean and Lave, 2003).

According to MacLean and Lave (2003) this simple notion of sustainability is not only unappealing, it is also too narrow. If, for example, the current generation develops a technology for mining poor ore bodies by using no more resources than are required today for rich ore bodies, the future generations will not be disadvantaged. Similarly, if the current generation develops alternative energy sources that are as inexpensive and non-polluting as extracting and burning petroleum, future generations will not be disadvantaged by current petroleum use. Thus, the more general notion of sustainability asks what opportunities will exist for future generations and whether their options will be less than those of the current generation. If the answer is that they will have at least as wide a range of options, then current activities would be described as sustainable. However, the range of opportunities includes environmental quality and recreational opportunities—which are as likely to be affected by the growth of population as the depletion of natural resources (MacLean and Lave, 2003).

Obviously, according to the definition in the Brundtland Report the hydrogen development path pursued in the U.S. today is not sustainable, since using fossil fuels for hydrogen production will impoverish the future fossil fuel supply. When we look at the more general notion of sustainability of MacLean and Lave we have to consider what opportunities will exist for future generations and whether their options will be less than those of the current generation. On the long term a transition towards a hydrogen economy is therefore sustainable, since it has the potential to be produced from renewable energy sources. Hydrogen creates the opportunity to fuel future societies 'forever'. The discussion becomes more problematic when you look at the short term, and especially when you take into account environmental quality, since the environmental advantages of hydrogen produced from fossil fuels are, as we have seen in section 6.1.2, disputable and uncertain.

The current generation and governments have the responsibility to take care of our planet and to maintain it for future generations. The hydrogen economy seems to be a good solution for the far future, but for the near future the benefits are disputable. Although the use of fossil fuels might be beneficial or necessary for the transition period, as claimed by many actors, we ought to avoid that these production methods gain a too large market share and become too important in the future. The risk of locking in these complex technologies need to be as small as possible. A focus on either more environmental benign hydrogen production pathways or on other effective technologies would be better. We should take action to create a livable healthy climate, now, and for the future generations. Despite changing trends, environmental views like this are, however, still trampled by economic aspects and by the interests of the influential industries.

6.2.2 Non Equal Playing Field

The non equal playing field that the government, by means of its budgets and focuses, but also by means of regulations and tax advantages etc, creates is seen as undesirable by many environmentalists and actors from the renewable industries. Reformers want governments to sweep away unfair advantages that prop up the established order through taxation, regulation, and technological standards. If governments level the energy playing field, the trend away from carbon could well resume. Carl Pope from the Sierra Club[59] and Ed Crane, head of the libertarian Cato Institute[60] state it as follows: "Environmentalists would be happy if renewable energy sources and energy-efficient technologies *were just allowed* to compete with the fossil fuels industry on a level playing field" (Vaitheeswaran, 2003) [emphasis added]. Bill Chameides of Environmental Defense, with their very pro market stance, agrees with this point of view and stated that "governments must be fair and must not favor *any* technologies."[61] Thomas Jackson, president of Milford, Connecticut-based Avalence, which is working on residential hydrogen electrolyzers, worries that federal incentives will go to the nuclear industry and strongly influence what would otherwise be a free market for new technologies. "There needs to be a level playing field that includes all the different approaches," Jackson says (Motavalli, 2003).

Proponents of the government subsidies and policy, however, claim that, as mentioned in chapter 4, an initial focus on, especially natural gas is necessary to get experience with hydrogen for the transportation sector. Moreover, coal is expected to become the cheapest source for hydrogen production. Renewable energy sources are simply not ready yet and there are still a lot of improvements necessary to produce cost-effective hydrogen and to fuel our future. In his famous article "Energy Strategy: The Road not Taken?" from 1976, Amory Lovins recognized the need for transitional technologies. According to Lovins we need one further ingredient for a coherent strategy towards renewable technologies: transitional technologies that use fossil fuels briefly and sparingly to build a bridge to the energy income economy of the future. This vision is shared by most environmentalists and renewable industries as well, and they realize that stopping the use of fossil fuels completely and immediately would be foolish and needlessly expensive, but according to them, this does not justify the huge advantages that fossil and nuclear industries get today. How long a transition period should take and a focus on transitional technologies is justified is often considered to be dependent on the development of the final technologies, in this case renewables. It can, however, take a long time before renewable hydrogen is cost-effective and the longer it takes, the bigger the chance that the transition technology is locked-in in the system. If coal and nuclear hydrogen plants are built, the 'transition' period will last for a long time. Large-scale, costly coal and nuclear hydrogen plants are not being built for a period of 10 or 20 years, but at least 50 years. So when many of them are realized the coming decades, the role for renewable hydrogen will remain small for most part of this century. The lock-in effect that comes with large, expensive technologies will make the situation even worse. This is

[59] The Sierra Club is America's oldest, and one of the largest and most influential environmental organization in the U.S. For more information see: http://www.sierraclub.org/

[60] The Cato Institute is a non-profit public policy research foundation. For more information see: http://www.cato.org/

[61] Data from interview with Bill Chameides, Environmental Defense

an important impact that needs to be taken into consideration in decisions about to what extent transitional technologies should play a role.

As has been discussed in the previous chapter, promises and expectations about technologies and their future profits play an important role in the allocation of federal subsidies and funding. Within a technology-stimulating approach, it makes sense to sponsor the most promising technologies, which for the near term are coal and nuclear based hydrogen. However, the risk of picking the wrong technology is high, even with the most promising technology. With an increased focus on promising renewable technologies, and with that creating an equal playing field, the chances are more spread out and the risks in general smaller. Moreover, private investments from industries will naturally focus more on fossil energy sources, since its low costs. Therefore the government would do better by accelerating R&D of renewable hydrogen production, and at the same time sweep away regulation, technological standards, etc. that favor established big industries.

The billions of dollars that the government is spending on the hydrogen transition is money that comes from the taxpayers. Little of this expenditure will directly benefit renewables. The government is 'subsidizing', or at least supporting, the big industries at the expense of the development of more environment friendly and thus more sustainable alternatives. This policy seems to be social unjust or unfair. Moreover, the public is also being misled by politics by justifying their policies as being a solution for the environmental problems. The before mentioned New York Times/CBS News poll from February 2006 regarding gasoline taxes, indicated that some people were concerned that a higher gasoline tax would find its way into what they considered the wrong hands. "If the tax is increased and oil companies reap the benefit, I would be against it" (Uchitelle and Thee, 2006). Thus, the current approach of the government seems not to be the preference of the public.

Obviously, the stakes in the current battle over hydrogen are high, but favoring fossil fuel and nuclear hydrogen technologies above renewables and with that creating a non equal playing field does not seem to be the right thing a government should do.

6.2.3 Centralized Production – Distribution Network

Centralized production of hydrogen is favored by most (fossil and nuclear) energy industries, because of costs, economies of scale, and the possibility of carbon capture and storage. Moreover, as we have seen in chapter 4, their scripts make centralized production more or less inevitable. The impact of centralized production and its required associated infrastructure on the environment and on society is, however, seen as negative by environmentalists and a large part of the population. According to Rick Zalesky, Vice President of Hydrogen Business at Chevron/Texaco, pipelines are often attacked or sabotaged by local residents and this is a bigger problem than terrorists' attacks on pipelines.[62]

Small-scale has several advantages over large-scale energy systems. According to Lovins (1976) it brings savings by virtually eliminating distribution losses, which are cumulative and pervasive in centralized energy systems. Small systems also avoid direct

[62] Data from interview with Rick Zalesky, Chevron/Texaco

"diseconomies of scale", such as the frequent unreliability of large units and the related need to provide instant "spinning reserves"; capacity on electrical grids to replace large stations that suddenly fail. Small systems with short lead times greatly reduce exposure to interest, escalation and mistimed demand forecasts – major indirect diseconomies of large-scale systems (Lovins, 1976). Moreover, according to Vaitheeswaran, (2003) a problem with large-scale centralized systems is that, because these projects have little accountability or transparency, they have typically been completed late, over budget, and with a far greater social impact than estimated, and they are usually run at far lower efficiency levels than promised. This problem is not as significant with small-scale.

The energy storage is often said to be a major problem of energy-income technologies. But, according to Lovins, this "problem" is largely an artifact of trying to recentralize, upgrade and redistribute inherently diffuse energy flows. "Directly storing sunlight or wind – or, for that matter, electricity from any source – is indeed difficult on a large-scale. But it is easy if done on a scale and in an energy quality matched to most end-use needs". On the whole, therefore, energy storage is much less of a problem in a decentralized energy economy than in a centralized one (Lovins, 1976). For Chevron, as one of the few 'fossil' companies that does not favor centralized production, yet, this is one of the reasons that they are focusing on a distributed hydrogen production system. "Large centralized hydrogen plants therefore need a lot of space for storage, while this space will be limited when distributed production is applied," said Rick Zalesky. In line with the storage problems, Chevron/Texaco is also worried about transportation problems. According to Jim Stevens, Catalyst Program Manager at Chevron/Texaco, the problems that rise with hydrogen transportation made Chevron decide to focus on distributed production. This turned out to be the best option for them. Rick Zalesky says that "since hydrogen is a completely different fuel than natural gas or oil, we think that the required infrastructure will be completely different as well. For oil and natural gas pipeline systems are good. For hydrogen, however, you need a much larger system, since the energy content per volume for hydrogen is almost three times lower than that for natural gas and oil. Moreover, the current pipeline system was built at the same time when the U.S. was developed. But how do we think we can build all those new pipelines now that the U.S. has been developed already?" Zalesky admitted, however, that when new technologies solve transportation problems of hydrogen, for example captured in a slurry in order to make it a liquid, "then decentralized hydrogen production goes out of the window for Chevron/Texaco as well."[63]

Thus, hydrogen has the potential to change our present rigid centralized petroleum system in a decentralized fuel system. This has many technical and economical advantages and avoids the construction of large, complex, costly and inefficient hydrogen production plants and an extensive distribution system. For fossil and nuclear industries these advantages do not really count though. Their scripts more of less require centralized production. Because of their power and influence in the transition process and in politics they can dictate the process and it is very likely that society has to face the disadvantages of a centralized fuel and energy system once again. Even the use of public money for pipeline construction in public-private partnerships is not unlikely for the future.

[63] Data from interviews with Rick Zalesky, Chevron/Texaco, and Jim Stevens, Chevron/Texaco

Apart from the technical and economical arguments, decentralized hydrogen production systems can have a positive impact on social structures as well. In the next sections I will first analyze the potential of hydrogen to avoid the creation of an oligopolistic fuel regime that is as powerful as the petroleum regime is today. After that I will further analyze the normative assessment of the impact ‘freedom’. These aspects create an interesting problem because they are higher order impacts that may lead to undesirable situations for involved actors, but are normally not foreseen during the development stage. Especially for ‘freedom’ ethical principles play an important role.

6.2.4 Oligopolistic Regime Structure

The petroleum regime has grown towards one of the most influential regimes societies have seen. Over the years, today’s actors in the petroleum regime have become ‘superpowers’ with an enormous influence on the economy and on politics. The petroleum industry is by far the largest business in the world and many other industries depend on them. Politicians are heavily sponsored by oil companies and the importance of oil for the American economy gives oil companies a strong influence in political debates and policy making. The few oil companies from the petroleum regime thus have a very powerful influence on the pressures from the landscape. In chapter 5 the processes that go on at the regime level have been discussed already and it shows that the rigidity of this regime makes it very difficult for alternative fuels and technologies, like hydrogen, to develop, gain market share and eventually take over petroleum.

In addition to the negative influence on the transition process, the fact that only a few companies control the petroleum supply and thus an important share of the economy, also has several negative impacts on our society. First of all, their size and market share result in a lack of competition, which is projected on market prices. The great French economist Leon Walras[64] (1834-1910), founder of the general equilibrium theory, outlined the conditions of competitive market equilibrium as follows (Ekelund and Hebert, 2003):

> “[…] an operation by which productive services are combined with natural agents to produce output that yields the greatest possible satisfaction of needs, under these two constraints: (1) that each service and each product has a single, market price at which demand and supply are equal; and (2) that the sales prices of each product are equal to their cost of production.”

“This condition [competitive equilibrium] is a condition of justice,” Walras added, “which it is up to social economy to establish.” Presumably this means that it is up to social economy to dictate the rules of the competitive marketplace (Ekelund and Hebert, 2003). The current situation at the petroleum market violates both of these key conditions, (1) and (2), as outlined in the above passage, and is therefore not a situation of justice. Recent years have shown enormous profits for oil companies, even at times when economic growth was minimal and many companies suffered losses. In the year 2005 a record for profits among American companies was set. With a profit of $36 billion it was Exxon Mobil that set the record. That year its overall profit climbed more than

[64] Leon Walras has been hailed by Joseph Schumpeter as “the greatest of all economists” (http://cepa.newschool.edu/het/profiles/walras.htm)

40% (Romero and Andrews, 2006). Huge profits like that indicate that the oil market does not see a competitive market equilibrium.

Apart from price related problems, another aspect that comes with the absence of competition is lack of innovation. Since competition is only small, companies have no incentive to put a lot of effort in innovation. This can be seen in the electricity industry, but a clearer example comes from telecommunications. Before the liberalization of telecommunications, the American market was completely controlled by AT&T. “The arrival of competition in telecommunications in the 1980s led to furious investments and innovation, helping to give rise to the digital economy. The forces of innovation, competition, chaos, and choice transformed yesterday’s sleepy telephone monopolies into today’s high-tech predators” (Vaitheeswaran, 2003). Since hydrogen was seen as the fuel of the future, competition for the (future) fuel markets increased significantly, because hydrogen can be produced from a variety of energy sources. Especially Shell and BP started to get involved in the development of hydrogen technologies and as with telecommunications the forces of innovation, competition, chaos, and choice can be seen in the fuel market.

Hydrogen has the potential to create a future fuel market that is highly competitive, which is beneficial for society. Because there is a wide variety of energy sources that can be used for hydrogen production, there are also many potential actors and technologies that *can* play a role in the hydrogen future, as we have seen in the previous chapters. This does not only have a positive influence on fuel prices and innovation processes, but it can also avoid that a few actors or technologies dominate the future fuel regime, which limits the power and influence of the regime significantly. By avoiding centralized production methods the advantages will be even better, since centralized production plants can become too important for local fuel supply and thus economy. This will give them much power in society and politics. A less powerful fuel regime would have a positive impact on our future society and on future developments, but the existing energy regimes – especially petroleum, but also coal and nuclear – will try to do anything to keep control and create an oligopolistic regime structure again. The fact that there are many potential actors, does thus not imply that a competitive market will actually be created.

The best way to avoid the creation of a new fuel oligopoly would be by decentralized micro-production of hydrogen. From section 4.3.1.8 it became clear that especially hydrogen from solar energy suits micro-production. As has been mentioned in section 4.1.2, in 1923, John Burden Sanderson Haldane stated that the great social advantage of adopting a hydrogen energy regime is that “energy will be as cheap in one part of the country as another, so that industry will be greatly decentralized” (Rifkin, 2002). This *vision* is embraced by Jeremy Rifkin. In his book ‘The Hydrogen Economy’ (2002) he describes the possible creation of a Hydrogen Energy Web (HEW) in which everybody can get into the hydrogen energy act and can be a consumer as well as a seller. In line with McDowall and Eames (2006) I call it a vision, since it represents a rather utopian, narrative description of a future hydrogen economy. Vision studies tend to be rhetorical rather than analytical. Their role is not to analyze or predict the future; the strength of the approach is that they expand the possibilities considered, and create a shared picture of what the future could be (McDowall and Eames, 2006).

According to Rifkin, since hydrogen is found everywhere on our planet and is inexhaustible if properly harnessed, every human being on earth, rich and poor, could be "empowered," making hydrogen energy the first truly *democratic* energy regime in history. Locating micro-power plants on-site with the end-user threatens the long-standing dominion enjoyed by centralized power plants that grew up with the fossil fuel era. A decentralized, hydrogen energy regime offers the hope, at least, of connecting the unconnected and empowering the powerless. When that happens, we could entertain the very real possibility of "reglobalization," this time from the bottom up, and with everyone participating in the process. Now, the end-user becomes its own producer as well as consumer of energy. When millions of small power plants are connected into vast energy webs, using the same architectural design principles and smart technologies that made possible the World Wide Web, people can share energy and sell it to one another – peer to peer energy sharing – and break the hold of giant energy and power companies forever (Rifkin, 2002).

The creation of decentralized HEWs connecting end-users can have positive impacts on our society. HEWs make the establishment of human settlements possible that are more widely dispersed and more sustainable in relationship to local and regional environmental resources compared to the mega cities that came with the fossil fuel era. The worldwide HEW, like the worldwide communications web, will allow us to connect every human being on the planet with every other in an indivisible and interdependent economic and social matrix. The human species can now become a human community fully integrated into the earth's ecosystems. Decentralized hydrogen production gives us the opportunity to make energy more democratic and to increase social equality worldwide (Rifkin, 2002). Today, according to Daniel Bell, we live in a society whose basic organizational, political, and economic structure increasingly tends toward technocracy, that is, the rule of institutions by a technical elite – engineers, economists, statisticians, scientists, management analysts, etc. – who are narrowly trained and specialized in specific functions, who seek to base institutional decisions on logic and quantification, and who view social institutions as social machinery (Perelman, 1980). Our future hydrogen society can be one based on humanism, instead of technocracy, and equal opportunities for all human beings can be created.

In conclusion, hydrogen has the potential to break down the oligopolistic regime structure that characterizes the petroleum regime and to avoid the creation of new ones. This will have a positive impact on future fuel markets, technological innovations and our society and it can result in a democratic energy system. Because of the power of the existing regime, many environmental and societal benign technologies – niche pressures – and policies – landscape pressures – have been demolished or impeded. The less oligopolistic a future regime is, the smaller the chances that this will happen again. The existing regimes will, of course, try to keep their control and power. Although the HEW is a vision and might be seen as a utopia, micro-production of hydrogen would clearly be the best solution for the avoidance of oligopolistic fuel and energy regimes. The main problem that micro-production faces is, not surprisingly, lack of support from the big energy companies and (thus) the government. Apart from the above mentioned technical, economic, and social advantages related to decentralized hydrogen production, another important social advantage can be pointed out: freedom.

6.2.5 Freedom

According to Lovins (1976) perhaps the most profound difference between the decentralized and centralized paths is their domestic social political impact. Both paths, like any 50 year energy path, entail significant social change. But the kinds of social change needed for a centralized path are apt to be much less pleasant, less possible, less compatible with social diversity and personal freedom of choice, and less consistent with traditional values than are the social changes that could make a decentralized path work. Although Lovins mentions that both energy paths entail social change, he does not really elaborate this statement. In this section I will analyze in what way the hydrogen economy can contribute to our personal freedom and, based on that, what direction is considered to be best from a (political) philosophical point of view. This section serves more as a philosophical reflection on personal freedom related to centralized hydrogen systems than as a normative assessment from the point of view of involved actors. The reason for that is simple; although personal freedom is a highly valued good in the U.S. and in many other countries, most people give little thought to the way daily things like electricity and fuel influence their personal freedom. Freedom from foreign oil and from governmental interference (liberalism) is what their concern is.

When it comes to large-scale capital investments, whether public or private, there are two different kinds of freedom at issue, according to Perelman (1980). The two historically often have been in conflict and they now have become increasingly incompatible. The two kinds of freedom are freedom A, or the freedom of integration, and freedom B, the freedom of differentiation. Differentiation is equivalent to autonomy, either of a coherent group or of an individual. Integration is the formulation and enforcement of the social contracts that binds individuals and groups together into larger communities, presumably for protection from the hazards to which the autonomous are vulnerable (Perelman, 1980). According to Perelman (1980), freedom A is, among other things, the freedom of mass consumption. Freedom A raises the economic pyramid and brings the poor into the middle-class.[65] Freedom A is the central concern of the liberalism of the 1930s, the liberalism of large-scale institutions. Freedom B, on the other hand, is the freedom of individualism, of self-reliance, of conservation; it is also the freedom of elitism, of cultural pluralism, of excellence, of beauty, of uniqueness, of ecological diversity. According to Swift (2001) a core claim at the heart of current liberal theory is that liberals are primarily concerned with freedom and autonomy of individuals. Liberals think that people should be free to choose for themselves how they live, apparently without regard to whether the choices they make are good ones, or how their free choices affect others. Freedom B is thus the principal concern of contemporary libertarianism.

Hydrogen is often called the 'freedom fuel' referring to the potential independence from foreign oil that comes with it, but how can this 'freedom fuel' contribute to our personal freedom? Before I will analyze 'freedom' related to both centralized and decentralized hydrogen production – and energy systems in general – I

[65] Although the whole economic pyramid rises, the top of the pyramid usually rises more. This increases the differences between poor and rich and it is this relative difference that is actually felt by the poor. According to Swift (2001) liberals often defend their theory by claiming that the size of the whole pie increases and with that also the piece of pie of the poor. They do not take into considerations the relative differences between poor and rich.

will first further elaborate the concept of autonomy, since autonomy is closely linked to personal freedom in moral philosophy.

Autonomy has evolved from the Greek terms autos ("self") and nomos ("governance" or "law"), used to refer to self governance in Greek city states. Autonomy has since come to refer to personal self governance: personal rule of the self by adequate understanding while remaining free from controlling interferences by others and from personal limitations that prevent choice. Autonomy, so understood, has been analyzed in terms of freedom from external constraint and the presence of critical internal capacities integral to self governance. However, autonomy has also been used to refer to individual choice, being one's own person, authenticity, and several other quite different notions (Beauchamp, 2001).

Beauchamp distinguishes three conditions for a satisfactory account of autonomy: (1) acting intentionally, (2) acting with understanding, and (3) acting free of influences that control behavior. The third of the three conditions must be treated separately and in greater detail than the other two. This condition requires that a person, like an autonomous political state, must be free of - that is, independent of, not governed by - controls, especially controls exerted by others that rob the person of self-directedness. This may be called the 'liberty condition'. Liberty is central to autonomy (Beauchamp, 2001).

Now what can be said about freedom related to centralized and decentralized hydrogen production pathways? As has been mentioned in section 6.1.1, in a centralized hydrogen economy, your lifeline does not come from an understandable neighborhood technology run by people you know who are at your own social level, but rather from an alien, remote, and perhaps humiliatingly uncontrollable technology run by a faraway, bureaucratized, technical elite who have probably never heard of you. Decisions about who shall have how much energy at what price also becomes centralized – a politically dangerous trend because it divides those who use energy from those who supply and regulate it (Lovins, 1976). The energy company serves the interests of big business rather than the interests of the public. In fact, with centralized hydrogen systems there is no change with the current situation, since today energy and fuel supply is centralized as well.

Clearly, there is little or no space for personal self governance in a centralized system. People have no choice but to buy their hydrogen from a centralized (fossil fuel) plant and they are not free from controlling interferences by these big businesses. No, or limited, understanding of the energy system creates a personal limitation that prevents choice. Moreover being one's own person, individual choice and authenticity are not stimulated at all.

Distributed, small-scale systems seem not to encounter most of these problems, at least not to the same extent. Consumers have more choice when it comes to where and from whom they get their hydrogen. Production on a more community or even individual based scale will result in a greater understanding of our energy system and has the potential to encourage the possibilities of self-development. This increases people's autonomy and thus freedom, choice, authenticity, etc.

Supporters of centralized systems use 'Freedom A' to defend their standpoint. According to them centralized energy systems are more reliable and access to energy is therefore ensured. Moreover, because of mass production and economies of scale, fuel prices are usually lower. Regarding hydrogen the argument can be like this: “since centralized systems are more reliable, consumers will always be able to get the hydrogen they need to keep their cars running. The reliability of decentralized systems is lower and if hydrogen supply stagnates, people cannot drive their car anymore and thus are less mobile and their freedom will be limited. Lower fuel prices give the consumer more freedom to spend its money on other things.” This is what Swift (2001) refers to as effective freedom. In contrast to formal freedom, effective freedom does not relate to not being interfered with by others, but involves being able to, or having the means to, do something. Effective freedom is promoted by cheap hydrogen, since this leaves the consumer with more monetary assets to do what they want to. Clearly, for most Americans, and many other populations, the freedom of mobility and effective freedom are more important than freedom in the sense of autonomy as described above. The enormous electricity blackouts in the U.S. in the late 90s and the beginning of this century show, however, that centralized power system failures are not something from the past and that the consequences and costs for society, and our freedom, are detrimental. With small-scale systems the consequences are limited, which has a positive impact on our freedom.

Apart from the preference for an increase in effective freedom over an increase in personal freedom, decentralized energy systems can encounter another problem regarding public acceptance. Although most people do want to control aspects of their lives that they feel closely related to or connected to, they do usually not want to worry about energy or electricity. This could be seen with the deregulation of the electricity markets in many countries. Deregulation was considered to be beneficial for consumers, but it resulted in many complaints and resistance from the public. People want electricity to run their different artifacts, but they do not care where it comes from and do not want to worry about choices they have to make between different suppliers, it just has to be there. With fuel the same applies. People just want to have it, but they do not want to think about where it comes from, or they do not want to have concerns about self-production. Therefore, in theory decentralized hydrogen production can have many advantages for society and the public, but in reality it is unlikely that the public is willing to accept an increase in worries and to take the responsibility for decentralized production.

Thus, although Freedom A and decentralized hydrogen production might be valued over Freedom B and decentralized production by consumers, Freedom B, and thus decentralized hydrogen production, is, from a moral point of view, more desirable. The rising popularity of, for example, organic food and home-schooling, might be a sign of increasing interest in Freedom B. People are willing to pay more in order to increase their freedom of individualism, of elitism, of uniqueness, of ecological diversity, etc. The U.S. government, despite its official commitment to individual freedom, does not, by focusing on centralized production systems, stimulate personal freedom and autonomy. It does, however, stimulate effective freedom, which can be justified since the public seems to favor effective freedom over personal freedom.[66]

[66] The distinction between effective freedom and personal freedom is in fact not as black and white as described here. Both freedoms can be more intertwined as stated here. Effective freedom, for example, can stimulate personal freedom: an increase in effective freedom can result in being able to pay for education, which can make a person more autonomous. In my discussion this is not really relevant though, since this is for most people not reality.

6.2.6 Conclusion

The assessments of the impacts by the different actors vary considerably. For most impacts there is a clear trade-off between economy on the one hand and the environment and society on the other. When it comes to environmental impacts, apart from environmentalists, economic interests usually have the upper hand in actors' actions and decisions. This is a cultural determined balance and the Bush administration is known for its strong preference for economic and political interests and not environmental. Among the U.S. population this preference is pretty strong as well, compared to other western countries. Although they might care about the environment, their personal economy is more important. The normative principle of standing up for your self-interests or organization's interest and the responsibility for economic growth seems to play a very important role. This does not only relate to environmental impacts, but plays a key role in all assessments of all impacts.

Our responsibility to take care of the environment and to create a sustainable society and future forms an important base for the hydrogen transition and its assessment as well. It is this normative principle that created a change at the landscape level, as discussed in chapter 4. The hydrogen economy seems to be a good solution for the far future, but for the near future we ought to focus either on more environmental benign hydrogen production pathways, or on other effective technologies. The governments focus, heavily influenced by industries, on fossil and nuclear production methods therefore seems not the right thing to do. Not only from an environmental point of view, but also because of the fact that the risk of picking the wrong technology is high, even with the most promising technology. With an increased focus on promising renewable technologies, and with that creating an equal playing field, the chances are more spread out and the risks in general smaller. Moreover, using public money for subsidizing big industries seems not to be supported by the public. The concerns related to the non-equal playing field are particularly addressed by small and renewable industries and by environmentalists. Regarding the equal playing field, the creation of equal chances for all technologies and a social just distribution of public money form the normative basis.

In addition to its potential to have a positive impact on the environment, hydrogen has the potential to change our present rigid centralized petroleum system in a decentralized fuel system. This has many technical and economical advantages and avoids the construction of costly and inefficient hydrogen production plants and an extensive distribution system. These advantages can have a positive effect on our society, but for fossil and nuclear industries these advantages do not really count though. Their scripts more of less require centralized production. Because of their power and influence in the transition process and in politics they can dictate the process and it is very likely that society has to face the disadvantages of a centralized fuel and energy system once again.

Apart from the technical and economical arguments, decentralized hydrogen production systems can have a positive impact on social structures as well. First of all, decentralized hydrogen production can break down today's oligopolistic petroleum regime and can avoid the creation of new ones. This will have a positive impact on future fuel markets and 'social just' prices, technological innovations and our society. Because of the power of the existing regime, many environmental and societal benign technologies – niche pressures – and policies – landscape pressures – have been demolished or impeded. Their power undermines the democratic norms and values that formed our society. The less oligopolistic a future regime is, the smaller the chances that this will happen again. Micro-production of hydrogen would clearly be the best solution for the avoidance of oligopolistic fuel and energy regimes. The main problem that micro-production faces is, not surprisingly, lack of support from the big energy companies – who benefit from an oligopoly – and (thus) the government.

Secondly, decentralized production has the potential to increase our personal freedom and autonomy, since consumers have more choice when it comes to where and from whom they get their hydrogen. Moreover, production on a more community or even individual based scale will result in a greater understanding of our energy system and has the potential to encourage the possibilities of self-development. From a moral point of view decentralized systems are therefore more desirable than centralized; they protect a person's autonomy and encourage her or his self-development. Reality is different though, for two reasons. First, in the U.S., and many other countries, effective freedom, or the freedom to be able to do things, is valued over autonomy. This freedom is claimed to increase with centralized systems. Second, decentralized hydrogen systems are likely to encounter public resistance, since the public just wants to have the energy and does not want to worry about the source. The non-willingness to accept the uncertainties or responsibilities that come with producing your own hydrogen can be a problem for decentralized systems.

7. Feedback

The hydrogen technologies, involved actors and their influences and (strategic) actions, and the assessment of possible impacts, have led to the last step of the TA: feedback to the technological developments. This feedback is meant to indicate technical and social actions that need to be taken in order to avoid or diminish negative consequences of the hydrogen transition and to stimulate positive ones. Moreover, it serves as a proposal for a social and political debate. For the feedback I revert to the multi-level perspective that played a central role throughout my research. The hydrogen transition can be steered by stimulating developments at the niche level, by putting pressure on the petroleum regime by causing changes at the landscape level, and by causing internal pressures in the regime. Co-evolutionary processes, on which the MLP is based, play, as we have seen in previous chapters, a key role in technological change, and therefore also in the feedback. As mentioned in section 2.1, apart from the development of alternative variations and the modification of the selection environment, Schot (1992) distinguishes one more general CTA strategy to alter current lines of technological developments: the creation or utilization of technological nexus. I will discuss this strategy as well.

7.1 Stimulation of Alternative Variations and Niches

There are many different possible variations when it comes to hydrogen production. The future dominant technology is not clear yet, so there are still a lot of opportunities to steer the developments. These technologies are, or will be, tested and demonstrated in technological niches and market niches and if successful they can move up to the regime level. In order to avoid negative impacts and stimulate positive impacts, it is therefore important that the right variations and niches are stimulated.

The impacts related to fossil and nuclear hydrogen and to centralized energy systems can easily be avoided by the development of *distributed renewable hydrogen production variations*. With (distributed) renewables the overall impact on the environment and sustainability is positive, an extensive distribution network is not necessary, the chance of the creation of new oligopolistic regimes is much smaller, and our personal freedom will be increased. Moreover, decentralized production systems are less complex and costly and therefore the involved risks are smaller. Renewable production pathways are, however, by far not cost-competitive yet, and several technical challenges still need to be overcome. Thus, for distributed renewable hydrogen to be considered as an alternative to fossil and nuclear hydrogen, significant technological improvements are necessary and production costs need to be substantially reduced.

The most promising renewable hydrogen production sources are wind and solar. Today wind energy is much more cost-effective than solar energy, but significant improvements are still needed to make wind-electrolysis-hydrogen systems cost-effective. Solar energy and hydrogen-from-solar faces more problems and is further away from commercial viability. Solar energy has the potential to meet global energy demand well into the future, though, and might be the best solution for a hydrogen economy. Not only because of its positive impact on the environment, but also because of its micro-production script, as shown in figure 21, that can result in social advantages and can avoid the creation of a new powerful fuel regime. Promising variations like the Tandem

Cell™, developed by Hydrogen Solar Ltd, the spectrum splitting approach and the Zinc oxide approach, but also new technologies and fundamental research therefore need to be stimulated more aggressively. It is important that the new decentralized production methods are developed in such a way that the consumer does not have to do much to keep the system running. As became clear from the previous chapter, the consumer in general just wants energy or fuel, but does not want to worry about how to get it.

Figure 21: Micro-production of solar hydrogen (Hydrogen Solar, 2006)

There is an important role for the government to stimulate these alternative variations and niches. Government leadership is considered to be critical in the hydrogen transition, because the current incentives for companies to make early investments in a hydrogen infrastructure are relatively weak, despite the many attractions of a hydrogen economy. Moreover, it is very unlikely that big energy industries, which have the monetary assets, will completely focus on renewables as long as they still have much to gain from their current energy source. Although companies like Shell and BP invest a lot in renewable energies, they also have an incentive to stick to oil and natural gas for the coming decades, as we have seen in chapter 5. Several smaller companies and research institutes put a lot of effort in the development of renewable systems, but because of their limited assets their impacts is relatively small. Governments can stimulate technological developments either by funding or by legislation.

In general governments fund, or try to develop, alternative variations which are not developed in the market. Examples from chapter 5 are the hydrogen infrastructure and the FutureGen project. Distributed renewable technologies are another example that needs governmental support, since the market naturally leans towards fossil energy sources. The government also should feel responsible to take care of our environment and to avoid the impacts that come with the current transition path. One of the recommendations of the in chapter 4 mentioned influential report of the National Academies is that “distributed hydrogen production systems deserve increased research and development investments by the DOE […] a program should be initiated to develop new concepts in distributed hydrogen production systems that have the potential to compete – in cost, energy efficiency, and safety – with centralized systems” (National Academies, 2004). According to this report, the government should thus stimulate the development of distributed variations and niches. According to Sperling (2002), the best way to stimulate these developments would be to support "small innovative technology companies and larger technology companies that are not already major automotive *[or energy]* suppliers; and universities, because of their expertise in basic research, but equally because they will train the industry engineers and scientists who will design and build these vehicles in the future." Apart from direct R&D funding, the government can also stimulate, and be involved in, the hydrogen development by just buying the new vehicles for their fleets and employees and thus influencing the market side. So far, the U.S. federal government spends large amounts of money on projects with big energy companies like BP, General Atomics and Southern Company though.

In addition to the stimulation of variations and niches, the government can also influence the selection environment of niches. This is what happens in several states or countries with subsidies or tax credits for hybrid cars, wind and solar energy for example. At the federal level a clear example of this in the U.S. is the wind energy Production Tax Credit (PTC). The PTC provides a tax credit of 1.5 cents per kilowatt-hour (adjusted for inflation, currently 1.9 cents) to the producer of electricity from wind energy. The PTC was an acknowledgement that wind energy can play an important role in the nation's energy mix. It was also a recognition that the federal energy tax code favors established, conventional energy technologies (AWEA, 2006). The PTC has boosted wind energy in the U.S. significantly over the last 5 years and seems to be an effective policy tool. Policies like this that create a favorable selection environment for new technologies, but also subsidies for renewable hydrogen and technology forcing regulations, can play an important role in the diffusion of renewable hydrogen as well and need to be implemented in market niches.

Since the U.S. government and the big industries are not likely to commit themselves to the development of distributed hydrogen production, there is a key role for the "small innovative technology companies and larger technology companies that are not already major energy suppliers; and universities" in stimulating the development of these variations. These companies should try to avoid that big companies will buy them up, and by forming alliances and coalitions they should concentrate their interest. Moreover, technological nexuses should be created and utilized, as will be discussed in section 7.3. These actors can also influence the selection processes.

Governments at state or city level can play an important role in the hydrogen transition as well. At state or city level there might even be more possibilities to promote more environmentally benign policy than at a federal level. Some states, not all, experience less influence from big energy companies, or have high renewable potentials. These states can have an incentive to pursue a hydrogen economy based on renewables, either because of economic and environmental reasons, or as a prestige project. A renewable hydrogen economy can become trendy and might cause the competition between states to become the first hydrogen economy. California is well known for its pursuit of environmentally benign policy, but they are not the only one. In 2000 Mayor Richard Daley, for example, has vowed to turn Chicago into "the greenest city in America" by getting a fifth of its power from green sources by 2006. Bill Abolt, at the time Chicago's environment commissioner, explained: "We decided we want power that is cleaner, cheaper, and produced close to home" (Vaitheeswaran, 2003). Twenty percent by 2006 seemed not to be feasible and the goal is now 2010, but Chicago is still one of the national leaders in the environmental movement (PBC, 2006).

To sum up, in order to avoid the negative impacts that come with the current transition path of fossil and nuclear hydrogen, distributed renewable hydrogen production variations need to be stimulated. Wind and solar are the most promising and especially solar has the potential to avoid the creation of another oligopolistic regime for the future. The government should stimulate the developments of renewable variations by funding small innovative technology companies and larger technology companies that are not already major energy suppliers and universities. Apart from funding it is crucial that the selection environment in niches is influenced by, for example, subsidies, tax credits and technology-forcing regulations. Stimulating decentralized hydrogen production can result in a significant pressure from the niche level on the petroleum regime.

7.2 Modification of the Landscape Level

The selection environment has a great influence on technological developments and apart from the selection environment within niches, changes at the landscape level have a huge influence. Again governments, both national and local, play an important role in the modification of the selection environment at the landscape level, but also the public has a great influence on the landscape level. I will discuss both separate, but both are in fact many times intertwined.

7.2.1 Governments

Governments have the power to regulate industries and to create favorable situations for environmentally friendly technologies. It is quite clear that technological changes cannot be forced by funding alone, and therefore many actors share the opinion that the government should aim for policy reforms that take away today's advantage for fossil and nuclear industries and that favor the development of alternative technologies and their adoption by the consumer. That will increase the pressure on, and the internal pressure of, the petroleum regime significantly.

According to Vaitheeswaran (2003), the $1.2 billion budget of the government will not do much to persuade industries that have hundreds of billions of dollars in sunk investments in fossil fuel technology (and which now plan to spend many billions more on oil exploration). Bolder moves – like an end to fossil fuel subsidies and carbon tax – are surely needed. Governments everywhere (but especially in America) need to send a powerful signal that we are entering a carbon constrained world. Whether this is done through carbon taxes, mandated greenhouse gas emissions restrictions, clever "cap and trade" market mechanisms, and so on is less important than sending a forceful and unambiguous signal. "Market forces offer a better (if not always politically popular) way to spur technologies. Therefore proper price signals need to be introduced" (Vaitheeswaran, 2003). In chapter 5 we saw that environmental organizations, especially Environmental Defense, also support market approaches. Environmental Defense considers a carbon dioxide cap and trade system as the best policy tool. Cap and trade systems are not new; in the 1990s America's trading system for sulfur dioxide, the main precursor to acid rain, was a huge environmental success. On the whole, America's sulfur dioxide trading system has been such a success in both economic and environmental terms that many parts of the world have been or are copying it. America has led the way in emissions trading, but other countries have gone much further when it comes to getting the prices of goods and services to reflect their true environmental impacts (Vaitheeswaran, 2003). Nevertheless, the experiences are present and cap and trade systems proved to be an effective policy tool to put pressure on industries within the regime from the landscape level.

Market-approaches like cap and trade systems might be useful for the reduction of greenhouse gas emissions, but they will not necessarily stimulate decentralized (renewable) hydrogen production. Market-approaches leave solutions up to the market, and the market is more likely to come up with nuclear and carbon capture and storage technologies, than with decentralized renewable technologies. Therefore just a market-approach will fail to avoid the negative impacts that come with centralized production methods. Technology-forcing regulations are thus required to make sure that the future will experience the benefits of decentralized sustainable energy systems. Environmental organizations would therefore do better when they not only focus on the important market-approach, but also try to stimulate certain technologies and technology-forcing regulations.

Changing the selection environment through regulation will be particularly successful if regulations are designed in such a way that the management of firms is able to anticipate them. The anticipation process is extensively discussed in chapter 4. Also, the standards must be set and remain unchanged for a long period of time, as well as be introduced in progressive stages (Schot, 1992).

7.2.2 The Public

In addition to policy reforms, another way to modify the landscape level is by altering the public's perceptive on and awareness of environmental issues, and issues related to (de)centralized production, like autonomy, oligopoly, etc. The public can have a great influence on both policy and politics and on industries. In the U.S., however environmental awareness and knowledge among the public, for example, seems to be, in general, but also compared to many other western countries, low. Brechin (2003) studied the cross-national public concern for global warming over a number of years. From this study the U.S. populace appears to be, like the Bush Administration's policy, "out of step" on climate change when compared to the citizens of a number of European countries. The largest publicly released cross-national study on the public attitudes toward global warming remains Gallup's study from 1993 (Brechin, 2003). This study shows that 47% of the U.S. respondents considers global warming a 'very serious' problem. In Germany that was 73% and in Great Britain 62%. Although this study is not up-to-date, more recent data regarding the U.S. alone shows that from 1989 till 2003 the public attitude has not changed much; during this period the percentage of the respondents that worries about the global warming problem a 'great deal' fluctuated around 30 (Brechin, 2003). In a 2001 study on knowledge about global warming, the citizens of Mexico led all fifteen countries surveyed with just 26% of the survey respondents correctly identifying that burning fossil fuels was the primary cause of global warming. The citizens of the U.S., among the most educated in the world, were somewhere in the middle of the pack at 15%. Germans and the British were more informed with 20 and 21%. Even the Cubans, at 17%, were slightly more informed than the American public (Brechin, 2003). Apart from the fact that the public can influence the government and industries and thus can cause pressure on the existing regime and policies, it is interesting to look at the question if the government and the industry are influencing American public opinion on global warming.

Where most European governments try actively to increase public environmental awareness, recent statements from 'whistleblowers' showed that the U.S. government tries to keep the public unaware of the seriousness of the environmental problems. An article in the New York Times of January 29, 2006 reports about how the Bush administration has tried to stop NASA scientist James E. Hansen from speaking out since he gave a lecture calling for prompt reductions in emissions of greenhouse gases linked to global warming (Revkin, 2006). An article in the Washington Post of April 6, 2006 indicates the same. "Scientists doing climate research for the federal government say the Bush administration has made it hard for them to speak forthrightly to the public about global warming. The result, the researchers say, is a danger that Americans are not getting the full story on how the climate is changing" (Eilperin, 2006). Employees and contractors working for the National Oceanic and Atmospheric Administration, along with a U.S. Geological Survey scientist working at a NOAA lab, said in interviews that over the past year "administration officials have chastised them for speaking on policy questions; removed references to global warming from their reports, news releases and conference Web sites; investigated news leaks; and sometimes urged them to stop speaking to the media altogether." "Their accounts indicate that the ideological battle over climate-change research, which first came to light at NASA, is being fought in other federal science agencies as well" (Eilperin, 2006).

Not only the government, but also industries are guilty of deceiving the public. Through public campaigns and intense lobbying, the Global Climate Coalition (GCC), an umbrella group representing heavy industry, like the fossil fuel sector, tried, since the late 90s, to persuade the public that the very notion of climate change was a hoax (Vaitheeswaran, 2003). The Greening Earth Society, a nonprofit group set up by American electric utilities promotes the idea that there is scientific doubt about the environmental harm of carbon dioxide. In a question-and-answer session on its website it stated: Q: Is Co2 a pollutant? A: No. CO2 is a fundamental building block for life on earth. Q: Are you taking the position that CO2 emissions from fossil fuel combustion are beneficial to life on earth? A: Yes. […] (Vaitheeswaran, 2003).

Although the government can, and should, play an important role in steering the developments in a favorable direction and avoiding negative impacts, it is thus not likely that the current U.S. government will commit itself to distributed renewable hydrogen systems or will try to increase the public's awareness related to environmental issues. Also big energy industries will not do that. Therefore it is important that pressure is generated from the bottom up and is felt by the government and the big industries. Environmental and public organizations, small companies, universities and political parties and politicians (especially Democrats), are the key actors that should stimulate this pressure and should try to influence the government and the industries.

Albeit the media is also influenced by money and big industries, it can play an important role in increasing environmental awareness among the population and in increasing the pressure from the bottom. However, it was only recently that an influential non-scientific magazine brought the topic to a wider audience: Time Magazine spent its April 3, 2006 edition on global warming and climate change. When this happens more and more and also in newspapers and on television the concerns will grow and people start feeling the need for action. Renewables can become trendy under a slogan like "Clean Air is so 21st Century!"[67] for example. Another important factor in increasing awareness can be seen very clearly today: rising oil prices. In the discussion about oil prices, environmental aspects are often mentioned today. In line with that, energy security has become an often debated issue in the media when it comes to oil. The increasing awareness of our dependence on foreign oil causes serious internal pressures in the petroleum regime and can have a positive effect on technological developments. In addition to the increase in awareness and knowledge about environmental issues in general, the public also needs to be educated on the impacts of the hydrogen transition and the impacts of a centralized system in an early stage of the developments. This change in awareness and knowledge, and thus in the selection environment, can have an important influence on politics and industries.

Apart from just increasing awareness and knowledge related to environmental issues and the hydrogen transition process, the landscape level and pressure can be changed by democratizing the technological developments.

7.2.3 Democratizing of the Technological Development

Changing energy systems is no simple matter; it is a complex and long-term process and it will require major and concerted efforts by governments, businesses, scientists, engineers, but also members of civil society. As has been discussed in chapter 6, decentralized hydrogen production has the potential to create a *democratic* energy regime, in which technological developments, policies, and energy supply are not ruled by a few powerful industries. In order to create this future, the development processes need to be democratized today already.

Bijker (1995) discusses the "democratizing of the technological culture" program and makes a distinction between the current 'thin democracy' and the 'strong democracy'. In a thin liberal democracy self-interest is the key; for the satisfaction of their needs citizens are not dependent on a community. The role of politics is to control this individualism (Bijker, 1995). A strong democracy is characterized by participation. According to political philosopher Benjamin R. Barber, author of the classic book 'Strong Democracy' from 1984, "strong democracy in the participatory mode resolves conflict in the absence of an independent ground through a participatory process of ongoing, proximate self-legislation and the creation of a political community capable of transforming dependent private individuals into free citizens and partial and private interests into public goods" (Bijker, 1995). This strong democracy plays a key role in the democratizing of the technological culture.

In a strong democracy the influence on agenda, design and implementation is shared. The participatory process of self-legislation rests on a balance between the (political) strategies of opposite groups and on listening to each other. As Barber states is: "'I will listen' means to the strong democrat not that I will scan my adversary's position for weaknesses and potential trade-offs, nor even (as a minimalist might think) that I will tolerantly permit him to say whatever he chooses. It means, rather, 'I will put myself in

[67] In 2001 this slogan was actually used by the nuclear industry as part of its stealthy campaign to steal the green high grounds (Vaitheeswaran, 2003).

his place, I will try to understand, I will strain to hear what makes us alike, I will listen for a common rhetoric evocative of a common purpose of a common good'" (Bijker, 1995).

To democratize the hydrogen transition, it is thus necessary that the different actors, including the public and environmental organizations, actively participate in the discussion and development process. So far Congress hearings and House hearings, for example, mainly showed testimonies from industries and research industries. Moreover, many (scientific) committees are formed to analyze the developments and to inform politics. These approaches correspond with thin democracy. For a strong democracy approach public debates, consensus conferences and "Citizens' Jury (Bijker, 1995) are more appropriate. These forms of public participation should be stimulated more. An additional advantage of involving the public is that their knowledge about the hydrogen technology and the different variations will increase. Bijker (1995) refers to this as a "higher inclusion" in the technical frame. This way the technology becomes more evident for the public and potential public resistance will decrease. Moreover, active citizenship will increase the pressures from the landscape level.

As with personal freedom and autonomy, it remains to be seen, however, if the public really wants to get involved in the hydrogen debate and developments. Active involvement can usually be seen with projects that influence a neighborhood, for example, directly as is the case with the construction of a highway for instance. This can happen with the hydrogen infrastructure as well, but as long as the impact of a new project or technology is not felt directly, it is unlikely that people are interested in active (democratic) involvement. Today democratic concerns among the public do exist related to say the war in Iraq, but not related to energy systems or petroleum. The increase of public's awareness of environmental issues, but also of the hydrogen transition process, is thus important for the democratization of the technological developments as well.

Thus, the pressure on the existing petroleum regime can be increased by using and stimulating landscape changes. The government plays an important role in that and with their regulations and policies they have a very powerful tool to increase pressure. The government, however, needs to be more influenced by other actors than just the big energy industries. Smaller companies, universities, environmental organizations, political parties, the public, etc. should play a role in that. Market-approaches seem favorable for the reduction of emissions, but in addition technology-forcing regulation is necessary to avoid that the 'market solution' goes toward centralized production systems again. The government experiences a strong influence from the petroleum regime and still favors actors in the regime and therefore it is important that a change in the public's perspective and behavior regarding environmental issues, and issues related to (de)centralized production, like autonomy and oligopoly, are stimulated as well. This landscape change, together with the democratization of the technological developments can influence both the government and industries.

7.3 Creation or Utilization of Technological Nexus

The improved and broader selection pressures from the selection environment will not necessarily result in clean technologies. To achieve this, requirements arising in the selection environment need to be linked with investment decisions taken in companies.

This is the task for the technology nexus (Schot, 1992). Today's most relevant nexuses related to the hydrogen transition are formed by car manufacturers as users, big energy companies as developers, and the government, mainly as regulator. Examples of this from chapter 5 are FreedomCar, the California Fuel Cell Partnership, FutureGen and the Nuclear Hydrogen Initiative. Relevant technological nexuses in which renewable industries are present seem to be absent. The creation of such nexuses, or the involvement of renewable industries in existing nexuses is important for the development of decentralized hydrogen production technologies.

Today the pressure from environmentalists and (small) renewable actors might be too diffuse and is not very influential. In order to increase the pressure on the well-organized and concentrated energy industries, the government, and their technological nexuses, it is important that coalitions are formed; concentrated interests tend to have much more influence in politics than diffused interests. Right now there are several societies, associations and organizations that try to promote renewables, or environmentally benign technologies in general. When these groups will form coalitions, their position will strengthen. This is why ASES initiated the Renewable Hydrogen Forum, but also why they joined the 25x'25 coalition. Although the specific focus of the 25x'25 coalition is not completely the same as the one of ASES, together they are stronger. Actors other than the big industries therefore should concentrate their knowledge and influence and should more actively look for partnerships, alliances and technological nexuses. The Renewable Hydrogen Forum, for example, could create a nexus with a small fuel cell or FCV producer, an environmental organization and a local (Democrat) government to learn from each other and to set up an experiment or niche market with decentralized renewable hydrogen production.

Coalitions and concentrated groups can increase their influence, and improve their position as a possible nexus member, by means of 'framing'. Frame analysis is concerned with the negotiation and (re)construction of reality by social/political actors through the use of symbolic tools. Frames are defined as symbolic-interpretive constructs. They include beliefs, images or symbols shared by people in a given society (Triandafyllidou and Fotiou, 1998). Framing literature seeks to understand and illuminate social movement processes like the generation, diffusion, and functionality of mobilizing and counter mobilizing ideas and meanings (Benford and Snow, 2000). So how can framing be used as a strategy for the hydrogen transition? Different people and especially different politicians have a different set of values and beliefs. Renewable energy sources are mainly introduced because of environmental reasons. However, it seems that environmental reasons are, especially to Republicans, of small interests. Reasons that are of interest are of economic nature, so by framing the policy instrument differently you might get support from more people. The biomass industry for example can create a lot of jobs, especially in rural areas. Many rural areas are mainly Republican, so by using a frame based on economic development more support is likely than just using a frame based on environmental issues. Renewable industries and environmentalists would do better if they frame their potentials in terms of economic aspects. With that their influence on the Bush administration will be larger than with just environmental focuses.

To conclude, the hydrogen transition can and should be steered by focusing on micro, meso and macro level and on both variation and selection processes. In order to avoid the negative impacts that come with the current transition path of fossil and nuclear hydrogen, distributed renewable hydrogen production variations need to be stimulated. The government should stimulate the developments of renewable variations by funding small innovative technology companies and larger technology companies that are not already major energy suppliers and universities. In addition to funding it is crucial that the selection environment in niches is influenced by, for example, subsidies, tax credits and technology-forcing regulations. The stimulation of these variations and niches can put a lot of pressure on the existing petroleum regime. This pressure, as has been discussed in previous chapters, can also come from the landscape level. Changes at the landscape level therefore need to be stimulated. The government plays an important role in that and with their regulations and policies they have a very powerful tool to increase pressure. Market-approaches seem favorable for the reduction of emissions, but in addition technology-forcing regulations are necessary to avoid that the 'market solution' goes toward centralized production systems again. The government experiences a strong influence from the petroleum regime and still favors actors in the regime and therefore it is important that a change in the public's perspective and behavior regarding environmental issues is stimulated as well. This landscape change can influence both the government and industries.

Because of the size, capital strength and huge economic and political influence of big energy industries, not only oil companies, but also coal and nuclear, it is very difficult to steer the hydrogen transition towards a more environmental and societal friendly system. The government, a powerful actor with the potential to steer it, is strongly influenced by these industries and it is very unlikely that their position and actions will change without feeling pressure from below. Steering the developments thus requires a bottom-up approach. Small companies, universities, politicians and political parties, the public, etc. need to put pressure on the government and on the big industries in order to be able to steer the developments. These groups that have either a less powerful and influential or a diffuse character should get involved in the hydrogen debate more actively and should create alliances, partnerships and technological nexuses.

Technological nexuses, as discussed in chapter 5, are required to link the changes in the selection environment with the variation processes. Today's nexuses only involve big energy companies. Relevant technological nexuses in which renewable industries are present seem to be absent. The creation of such nexuses, or the involvement of renewable industries in existing nexuses is important for the development of decentralized hydrogen production technologies. By not involving only them, but also increasing the active participation of the public and of environmental organizations in the discussion and development process, the hydrogen transition can be democratized and the pressure from the landscape level can be increased.

8. Summary and Conclusion

The world is at a crossroads. Decisions taken in the next few years about energy in big countries like the United States will shape investments made in energy infrastructures around the world for a generation or more. The 21st century gives us the opportunity to develop technologies that can cause a transition from the polluting fossil fuel transportation era to a clean hydrogen future; now we only have to seize this opportunity and make sure that we aim the technological change towards the right direction. In my research I have conducted a Constructive Technology Assessment (CTA) on the infrastructure related to the hydrogen economy, in order to identify technology induced impacts, and to present alternative decision oriented options to steer the developments of the technology in the 'right' direction, away from undesirable impacts.

Systems Innovations and MLP

The systems innovation approach, and its multi-level perspective, used as a conceptual model in this research, distinguishes three levels within technological changes (see chapter 2). First, the micro level of technological niches, in which radical innovations are generated. Second, the meso level of technological regimes, which is defined as 'the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems - all of them embedded in institutions and infrastructures', by Rip and Kemp (1998). The third level is the macro level of socio-technical landscapes, which consists of a set of deep structural trends external to the regime. Within system innovations co-evolution plays an important role. Co-evolution is the linked evolution of two dynamics, each of which can be conceptualized in terms of variations – the content or technology – and selections – the context or environment.

The multi-level perspective (MLP) has been used to understand the emergence and diffusion of new technologies. An important point of the MLP is the dynamic interaction between the multiple levels. Novelties emerge in niches in the context of existing regimes and landscapes with its specific problems, rules and capabilities. Niches are crucial for transitions and system innovations, because they provide the seeds for change. If technologies become successful in niches, they will put a lot of pressure on the regime level and eventually the emergence of a new technological regime is possible. Success of a new technology is not only governed by processes within the niche though, but also by developments at the level of the existing regime and the sociotechnical landscape. System innovations occur as the outcome of linkages between developments at multiple levels. Changes at the landscape level, for instance, may influence the development of technologies embedded in regimes as well as new promising alternatives by putting pressure on the regime, and creating 'windows of opportunities' for new technologies.

Pressures in and from the Hydrogen Transition

In the U.S., and in most other developed countries, three important aspects that put pressure on the petroleum regime – the regime that plays a key role in the hydrogen transition and was the main focus of my research – can be seen today. These are environment, peak-oil, and geopolitics, with energy security as the main concern related to oil. These issues put pressure on the regime from both the landscape level, as from within the regime itself. These pressures influence the development of technologies embedded in regime as well as new promising alternatives by creating the 'windows of opportunities' for new technologies. The petroleum regime cannot solve the problems related to the three above mentioned aspects, and a demand for alternative fuels was created. Hydrogen was seen as a promising alternative and it became as popular as it is these days in the U.S., and worldwide.

Its abundance, energy content, potential to be a pollution free fuel, and the fact that it can be produced from a variety of (domestic) energy sources, make hydrogen an interesting option for substituting oil and driving our future economy. However, hydrogen is not an energy source, but an energy carrier, like electricity. Therefore it needs to be produced by using other energy sources.

Influenced by the developments at the regime and landscape level many different hydrogen production technologies were, and are, explored and developed. Many of these variations are promising and it is too early to tell which variation(s) will become the dominant technology(ies), but most likely hydrogen will come from multiple feedstocks. The expectations are that natural gas will be the dominant technology in the near-term, in the mid-term coal and nuclear hydrogen technologies will join natural gas and only in the very long term renewable hydrogen technologies are expected to become the dominant technology. If a certain technology has the potential to become dominant does not only depend on the characteristics of the technology, but also on the *selection* environment, the context. During the development of variations, hydrogen technology developers try to anticipate on the present and future selection environment. Four aspects seem to play a role in the anticipation process related to hydrogen developments are: market; environment (including 'dirty reputation'); legislation; and developments of and expectations about technologies. In addition to the anticipation processes, technological nexuses play a role in variation and selection processes related to hydrogen technologies. Institutional links between hydrogen developers – especially oil companies – car manufacturers as hydrogen users, and the government as regulator and developer are formed to actively link the variation and environmental selection processes. Within these nexuses the different actors all articulate their interest, technologies, policy, etc. in order to learn from each other. Technological nexuses also exist between developers, governments, and other groups like environmental organizations, either in joint projects or in extensive contacts and lobby processes.

The new developed technologies put a significant pressure on the existing regime. Some of the hydrogen technologies are being tested in market niches already. These niches are, however, very small and limited. Most pressure on the petroleum regime is therefore caused by the articulation processes regarding promises and expectations about technologies. These expectations show a self-fulfilling and self-justifying process and hydrogen became the subject of a strategic game. Expectations and promises related to hydrogen create '*prospective structures*'; actions become coordinated through the prospect of a new technology and its functions while this emerging configuration is simultaneously shaping the technology to be.

Promises and Expectations

Prospective structures are actively created by actors involved in the hydrogen transition by means of articulation processes. In the late 1990s that automotive and oil companies started to articulate promises and raise expectations about the fuel cell and hydrogen technologies. Expectations and promises were now shared among the two most influential industries in the transportation sector and the articulation of expectations created a prospective structure. These stories and structures created new patterns and institutions and the promising technologies were taken up in the industries' agendas. The oil and car industries started to join and form groups and partnerships and even established subsidiary companies. Stimulated by the articulation of promises and expectations by the car and oil industries, soon other energy industries, especially the nuclear industry, got interested in hydrogen technologies and started to articulate their own promising technologies and expectations. These processes caused a rise in interest in politics as well and led to the Hydrogen Initiative and its $1.2 billion budget.

The articulation of promises and expectations play a very important role in technological change. The prospective structures that are created are forceful due to the perceived implications of the projected future. These articulation processes therefore cause a significant pressure on the existing regime and are an important strategic move for new actors. These parties construct and communicate positive expectations in order to make other actors believe that it will yield returns in future and to get support. The prospective structures therefore do not only have an impact on the agenda of the actor that creates them, but also on the agenda of the actors that pick up the structures and start to believe in the promises and technologies. This is what can be seen in the federal funding of hydrogen projects. Based on the promises and expectations, and the articulation of it by actors – not only actors from industries, but also scientists from the government for example – the government and the Department of Energy (DOE) allocate the budgets. Very promising technologies, which are expected to yield returns in future, are more likely to receive money than technologies of which the future profit is more uncertain are. The importance of articulating promises and expectations was recognized by the American Solar Energy Society (ASES) as well, and although they do not even particularly support a hydrogen transition, they articulated their own promises and expectations in order to protect their federal budgets. Thus, articulation processes are crucial for actors in order to play a role in the hydrogen transition.

The Petroleum Regime

Although the actors of the petroleum regime are actively involved in the hydrogen transition and were among the first actors that started to articulate promises and expectations, they have a strong incentive to control the transition process and even slow it down. This happens at all three levels of the transition process. By improving existing oil production technologies and developing new production methods, the position of the petroleum regime is tried to strengthen again and the internal pressures of peak-oil and foreign energy are tried to solve. At the landscape level, oil companies strongly influence politics by putting pressure on it. That way they try to avoid legislation that will harm them. This power in politics is, like the articulation of promises and expectations a very important aspect of technological change. At the micro-level, oil companies buy up small successful companies to avoid their further success and thus decrease the pressure on the regime. Because of their size, economic importance and capital strength the influence of the actors in the existing petroleum regime on the transition process is very strong. The transition to clean energy will not happen overnight and the oil industry is unlikely to fade from the scene anytime soon.

Impacts from the Hydrogen Transition and its Assessments

The most likely production methods that will emerge as dominant paths in the U.S. are natural gas for the short term, coal and nuclear for the mid-term and renewables only for the very long term. These paths are not only the preferred paths of the big industries; the U.S. government strongly favors these paths as well. There are several important impacts that follow from the centralized fossil and nuclear hydrogen path, of which the most relevant from a CTA point of view are 'environment and sustainability', the related to this 'non equal playing field', and the, to centralized production related, impacts, 'distribution network', 'oligopolistic regime structure', and 'freedom' (see chapter 6).

The assessments of the impacts by the actors vary considerably per actor (group). For most impacts there is a clear trade-off between economy on the one hand and the environment and society on the other. When it comes to environmental impacts, economic interests usually have the upper hand in actors' actions and decisions. This applies for industries, the government, as well as the public.

The responsibility to take care of the environment and to create a sustainable society and future forms an important base for the hydrogen transition and its assessment as well. It is this normative principle that created a change at the landscape level, as discussed in chapter 4. The hydrogen economy seems to be a good solution for the far future, but for the near future we ought to focus either on more environmental benign hydrogen production pathways, or on other effective technologies. The governments focus, heavily influenced by industries, on fossil and nuclear production methods therefore seems not the right thing to do. Not only from an environmental point of view, but also because of the fact that the risk of picking the wrong technology is high, even with the most promising technology. With an increased focus on promising renewable technologies, and with that creating an equal playing field, the chances are more spread out and the risks in general smaller. Moreover, using public money for subsidizing big industries seems not to be supported by the public.

Hydrogen has the potential to change our present rigid centralized petroleum system in a decentralized fuel system. This has many technical and economical advantages and it avoids the construction of costly and inefficient hydrogen production plants and extensive distribution systems. Moreover decentralized systems have social advantages. First, it can break down today's oligopolistic petroleum regime and can avoid the creation of new ones, which will have a positive impact on future fuel markets and 'social just' prices, technological innovations and our society. Because of the power of the existing regime, many environmental and societal benign technologies – niche pressures – and policies – landscape pressures – have been demolished or impeded. Their power undermines the democratic norms and values that formed our society. The less oligopolistic a future regime is, the smaller the chances that this will happen again. Second, it has the potential to increase our personal freedom and autonomy, since consumers have more choice when it comes to where and from whom they get their hydrogen. Moreover, production on a more community or even individual based scale will result in a greater understanding of our energy system and has the potential to encourage the possibilities of self-development. From a moral point of view decentralized systems are therefore more desirable than centralized; they protect a person's autonomy and encourage her or his self-development. Reality is different though, for two reasons. First, in the U.S., and many other countries, effective freedom, or the freedom to be able to do things, is valued over autonomy. This freedom is claimed to increase with centralized systems. Second, decentralized hydrogen systems are likely to encounter public resistance, since the public just wants to have the energy and does not want to worry about the source. The non-willingness to accept the uncertainties or responsibilities that come with producing your own hydrogen can be a problem for decentralized systems.

The above mentioned advantages can have a positive effect on our society, but for fossil and nuclear industries these advantages do not really count though. Their scripts more of less require centralized production. Because of their power and influence in the transition process and in politics they can dictate the process and it is very likely that society has to face the disadvantages of a centralized fuel and energy system once again.

Steering the Developments

In order to avoid the negative impacts that come with the current transition path of fossil and nuclear hydrogen, current policies need to be changed. The insights of the technology assessment resulted in several policy advices, as described in chapter 7. Measures can be taken at the different levels of the multi-level perspective. At the micro-level distributed renewable hydrogen production variations and niches need to be stimulated, especially hydrogen from wind and solar energy. The government should stimulate the developments of renewable variations by funding small innovative technology companies and larger technology companies that are not already major energy suppliers and universities. In addition to funding it is crucial that the selection environment in niches is influenced by, for example, subsidies, tax credits and technology-forcing regulations. The stimulation of these variations and niches can put a lot of pressure on the existing petroleum regime. This pressure, as has been discussed in previous chapters, can also come from the landscape level. Changes at the landscape level therefore need to be stimulated. The government plays an important role in that and with their regulations and policies they have a very powerful tool to increase pressure. The government, however, needs to be more influenced by other actors than just the big energy industries. Smaller companies, universities, environmental organizations, political parties, the public, etc. should play a role in that. Market-approaches seem favorable for the reduction of emissions, but in addition technology-forcing regulations are necessary to avoid that the 'market solution' goes toward centralized production systems again. The government experiences a strong influence from the petroleum regime and still favors actors in the regime and therefore it is important that a change in the public's perspective and behavior regarding environmental issues, and issues related to (de)centralized production, like autonomy and oligopoly, are stimulated as well. This landscape change, together with the democratization of the technological developments can influence both the government and industries.

Technological nexuses, as discussed in chapter 5, are required to link the changes in the selection environment with the variation processes. Today's nexuses only involve big energy companies. Relevant technological nexuses in which renewable industries are present seem to be absent. The creation of such nexuses, or the involvement of renewable industries in existing nexuses is important for the development of decentralized hydrogen production technologies. By not involving only them, but also increasing the active participation of the public and of environmental organizations in the discussion and development process, the hydrogen transition can be democratized and the pressure from the landscape level can be increased. If the public actually wants to be more involved in the developments is disputable and remains to be seen.

The transition process is a very complex process and is difficult to steer. On the one hand the problems and uncertainties with the energy source of the powerful petroleum regime feed the transition and create windows of opportunities. On the other hand, because of the size, capital strength and huge economic and political influence of big energy industries, not only oil companies, but also coal and nuclear, it is very difficult to steer the hydrogen transition towards a more environmental and societal friendly system. The government, a powerful actor with the potential to steer it, is strongly influenced by these industries and it is very unlikely that their position and actions will change without feeling pressure from below. Steering the developments thus requires a bottom-up approach. Small companies, universities, (left-wing) politicians and political parties, end-users, the public, etc. need to put pressure on the government and on the big industries in order to be able to steer the developments. These groups that have either a less powerful and influential or a diffuse character should get involved in the hydrogen debate more actively and should create alliances, partnerships and technological nexuses and should try to mobilize people. Vision studies like Rifkin's Hydrogen Energy Web, as discussed in chapter 6, can play a role in this as well. The question remains, however, to what extent these actors can increase the pressure on governments and industries and can influence the developments. Even if these actors are getting more involved in the transition process and if, for example, politicians are trying to mobilize people, it is not likely that the government, other politicians and industries will remain silent and they will probably start trying to influence the public and other actors again.

Although the developments and actions that can be indicated regarding hydrogen technologies are numerous and the image is created that hydrogen is our inevitable future, it is not certain yet if our future indeed will see a hydrogen economy. Many companies got involved in the hydrogen developments because of business strategy reasons. For car industries this can be in order to create and enter new markets as the first company or in order to justify the delay of increased fuel efficiency standard, for example. For oil industries, hydrogen has strategic value, because they see the key role they can play, something that was not the case with battery electric vehicles. Other energy industries also realized their possible future role in the supply of hydrogen and from a business point of view hydrogen became interesting. Many developers see hydrogen as one of their bets and hydrogen became 'hyped' as Romm (2004) claimed. Despite, or because of, its potential and popularity hydrogen might indeed be a hype that soon will disappear. Today it seems very promising, but these promises and expectations might turn out to be false. Moreover, new technologies, or changes at the landscape level can influence the hydrogen developments and might result in the disappearance of it from the scene, as happened with the battery electric vehicle. Thus, it is possible that we cherish false hope in hydrogen and that the focus on hydrogen is a strategic move today, but a fools mate tomorrow.

MLP and CTA

The use of the MLP as a basis for a CTA is very useful. A clear understanding of transition processes and the influences at the different levels creates a strong framework to analyze the different steps of a CTA. The role of expectations and promises is a very important one in the hydrogen transition and a special focus on prospective structures and articulation processes was a valuable addition. Apart from exploring the technological developments, the social actions at the different levels, and, to a lesser extent, the possible impacts, MLP is a helpful tool to come up with recommendations for possible ways to influence the development process. However, the MLP was not appropriate for all aspects of the CTA and during my research I encountered some problems with it.

First, one of the steps of the CTA was the normative assessment of the technology. Within systems innovations and the transition theory, normative principles do not get particular attention in the transition processes, however. The transition literature explores and analyzes the way technological changes occur, without looking at an assessment of these changes. Implicitly normative principles might play a role in the transition literature. From the literature that I have used it became clear that the transition theory is often used in the analysis of regime shift towards sustainability. Kemp et al (1998), Rip and Kemp (1998), Elzen et al (2004), Hoogma et al (2005), all focus on sustainable technologies. The normative principles of taking care of our environment and creating a sustainable society are very important and relevant principles, but other normative principles can be of importance as well and one would do good to take these into consideration as well. In the case of the hydrogen transition, for example, hydrogen might contribute to our sustainability goals, but if a centralized production system is realized, then the potential of creating a democratic energy system is undermined. The normative principle of sustainability will thus be in conflict with the normative principle of creating a democratic energy system. These mutual relations between different normative principles may need to get more attention in the transition theory.

Second, although the main focus in my research was on the petroleum regime, I soon experienced the complexity of different regimes that were intertwined. Apart from the petroleum regime, the transportation regime, the electricity regime, and even the battery regime play an important role in the hydrogen transition. Of these, especially the internal combustion engine regime and the transportation regime were closely linked to my research. Elzen et al (2004) focus solely on transitions in the transportation regime, and in my research I kept, although my focus was on hydrogen as a transportation fuel, the petroleum regime more or less isolated from the other regimes. However, it might be more relevant and interesting to consider the different closely linked regimes together when analyzing transition processes. For that the role of other regimes may need to get a more prominent position in the transition theory and in the MLP.

Third, it became clear that the petroleum regime has a great influence not only on the transportation sector, but on our economy and society in general. Oil, or fuel in general, drives almost every industry and influences all our private lives. The petroleum regime might be the most powerful regime we have ever seen in our society and there influence on the landscape level is clearly visible. Although in MLP literature it is often stated that individual regime shifts will not affect the landscape dramatically, the transition from petroleum to hydrogen definitely has the potential to affect the landscape dramatically. Fuels will remain the driving force behind our economy and society, and if hydrogen is produced in the environmental, decentralized ways, at the landscape level it can change our environmental and geopolitical concerns and can even have a positive impact on our political structure. This potential impact on the landscape level might not be direct, since, as stated before, this single regime shift will cause many others, which together influence the landscape. However, it is still our dependence on fuel that causes the effect.

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Appendix A

For my semi-structured interviews, a view questions were formulated on forehand. These questions formed a start for the interviews and served as a guideline for making sure the right information was acquired.

? Why are you or is your company working on hydrogen?

? Do you believe in hydrogen?

? What are your expectations?

? What is your organization doing to get involved or steer developments?

? What do you think about centralized versus decentralized hydrogen production methods?

? What needs to be done to steer or stimulate the hydrogen transition or certain technologies?

? Is the current development direction the best way? Why/why not?

? How do you assess the possible impacts of the current transition path?

? What problems do you foresee with hydrogen or with certain production methods?

? Why shouldn’t we focus on other technologies to reduce oil dependency or emissions?

? What do you think of the role of renewables in the transition process, now and in the future?