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CHALLENGES IN THE TRANSITION TOWARD A HYDROGEN-BASED SOCIETY: AN IN-DEPTH STUDY TO ASSESS THE POTENTIAL OF A TRANSITION TO A HYDROGEN-BASED ENERGY SUPPLY IN EUROPE

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The Hysociety project, financed under the FP5 framework of the European Commission, aimed to contribute to European policies on hydrogen-related issues through the development of an action plan for the introduction of hydrogen. The geographic target was Europe, focusing on the 15 European Union member states, plus Norway and Iceland. In addition, demonstration projects in Canada, the United States, Japan, Brazil, and China were analyzed. Work package 1 addressed the technological, infrastructural, ecological, economic, political, and cultural challenges of the transition to a hydrogen-based society. The work built upon an analysis of the challenges identified in demonstration projects in all participating countries. In this article we first discuss the transition theory and the methodology used in Hysociety work package 1 and conclude with a discussion of results of the Hysociety project.

Keywords: **[AuQ2]**

INTRODUCTION

In many studies the technical feasibility of the use of hydrogen as an energy carrier in transport and energy sectors has been assessed. It is often argued that hydrogen holds the potential to provide a clean, reliable, and affordable energy supply. In addition, hydrogen is often depicted as potentially enhancing economies, the environment, and security of supply because it can be produced from a variety of resources and can offer near-zero emissions of pollutants and greenhouse gases. As the share of renewable intermittent energy increases, hydrogen can play an important role as a buffer in matching energy demand with energy supply. Global concerns about climate change and energy supply securities have now created a forum where the widespread penetration of hydrogen-based technologies is discussed.

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Until recently, however, there existed no European road map or action plan that identified the coordinated, long-term public and private efforts required to solve the challenges that hinder a widespread transition to a hydrogen-based energy supply. The need for such an action plan led to the formulation of the Hysociety project proposal. Hysociety is coordinated by IST (Portugal) and involves research institutes in Portugal (IST, SRE), Norway (SINTEF, RF), Finland (VTT), Spain (INTA), Belgium (VITO, ULg, AVERE), Germany (VGB, FhG/ISI, LBST), Austria (EVA), Sweden (SYDKRAFT), Italy (ENEA), the United Kingdom (ICSTM), France (CNRS-LCSR), Greece (NTUA), Iceland (INE), and the Netherlands (ECN)[AuQ3]. More details about the Hysociety project can be found at http://www.hysociety.net. Let us first briefly identify what is meant by the "transition to a hydrogen-based society." The scope of this article does not allow an in-depth discussion of the transition theory. For a detailed description of this theory we refer the reader to Rotmans (2003), Hoogma *et al.* (2002), Geels (2002), Rotmans *et al.* (2000), Kemp, Schot, and Hoogma (1998), and Schot, Hoogma, and Elzen (1994).

TRANSITION TO A HYDROGEN-BASED SOCIETY

To analyze the challenges that the transition to hydrogen-based energy supply is faced with, the Hysociety work package 1 built on insights from transition theory as developed in several Dutch universities (Rotmans, 2003; Hoogma *et al.*, 2002; Geels, 2002; Rotmans *et al.*, 2000; Kemp *et al.*, 1998; Schot *et al.*, 1994). In this theory a transition is defined as a gradual and lengthy process (25–50 years) of change in which a society or system changes fundamentally. The theory claims that transitions typically start with the breakthrough of several radical technological or social innovations from their technological or market niches (the micro level). In transition theory, technological niches are defined as protected spaces where technologies or concepts are developed. The innovations are protected by various actors who believe in their long-term prospects and/or profits and who are willing to invest time, effort, and/or money. A market niche denotes a subsection of a larger market that can survive economically, while a technological niche cannot and needs economic protection. Innovations can only outgrow their niches when they are able to couple with developments in the existing dominant technological regime (the meso level). Examples of regimes are the regime of energy supply, the regime of agriculture, and the regime of transport by ship. Developments in the wider context of a regime — the landscape (the macro level) — can also influence the breakthrough of an innovation. Examples of events on the macro level are the nuclear disaster in Chernobyl and processes such as liberalization and individualization. Transitions are thus the result of a complex interplay between all three levels: niche, regime, and landscape.

Several phases can be distinguished in the transition process (Rotmans *et al*., 2000). The first phase is the predevelopment phase: There is very little visible change in the regime, but there is a lot of experimentation in niches. In the second phase, the takeoff phase, the process of change gets underway. The innovation starts to interfere with the regime from within the niche. This results in the third phase, the acceleration phase, characterized by structural changes on the regime level taking place in a visible way through an accumulation of sociocultural, economic, ecological, and institutional changes that interact. The introduction of hydrogen-fuelled cars, for instance, will have impacts on infrastructure; assumptions about regular, conventional driving; and governmental regulations. In this third phase, collective learning, diffusion, and embedding processes occur. In the last phase, the stabilization phase, the speed of social change decreases, and a new dynamic equilibrium is reached.

As mentioned earlier, a transition typically starts from a technological or market niche. A pathway for scaling up hydrogen use could thus strategically build from the existing hydrogen technological and market niches. Therefore it is important first to assess the current technological practices of hydrogen production, distribution, storage, conversion, and end use. For a more detailed discussion of the state of the art of different hydrogen technologies, we refer the reader to Veziroglu and Barbir (1998), Gregoire-Padro and Putsche (1999), Barbir (2001), U.S. Department of Energy (DOE) (2003), and National Academy of Sciences (2005).

Owing to the scope of this article, below you will find a selected and brief description of current practices of hydrogen as discussed in two vision and road map papers from the U.S. Department of Energy (DOE) (DOE, 2002a, 2002a,b). These road maps are used as a base to assess the current state of the art of hydrogen technologies, for the simple reason that there are no European road maps available yet. In intermezzos we will highlight those aspects of a transition to a widespread hydrogen society that have been taken into account in the Hysociety project.

EXISTING HYDROGEN PRACTICES

From Small-Scale, Decentral Production via Centralized Production of Hydrogen to Large-Scale, On-Site Production

Today, hydrogen production technologies are in commercial use by the chemical and refining industries, which produce tons of hydrogen per year in a limited amount of plants. One perspective on the transition to widespread implementation of hydrogen, mentioned in the DOE hydrogen road maps (DOE, 2002a, 2002a,b), is that the first stage will involve decentral hydrogen production accommodated by a supply network that will evolve from the existing fossil fuel-based infrastructure. The next stage envisioned in the road maps will include large, centralized hydrogen production facilities, such as large refineries in industrial areas, power parks, and fuelling stations in communities. Mid-sized community systems and a supply network will accommodate these production facilities. In the final stage, so the road maps claim, the on-site production of hydrogen at customers' premises will take flight.

Although the DOE road maps sketch an interesting pathway, its actual potential is difficult to assess since no information is given on how to reach this vision. In fact, it is merely a technology vision, not a pathway or road map, since it offers no actual map but simply assumes many changes without identifying them. Who will, for example, invest in the initial decentralized production of hydrogen or in the second or last stage of the transition? Who will be the primary actors in all stages? In the pathway a big shift in end-use application is assumed, a shift that is directly linked to the production facilities. If the future of hydrogen application is to be found in the energy, and specifically the transport sector, new actors will have to emerge, new infrastructures will have to be built, and new codes and standards will have to be installed. Who will coordinate all these actions? These questions, and an even wider array of societal aspects, have to be identified and assessed before a transition can successfully be managed.

The Hysociety project tackles these aspects and acknowledges that transitions need to be managed through all four stages and not be limited to managing only the technological aspects. The superiority of a new technological option and market mechanisms are not a sufficient guarantee for a successful transition. The technological promise is, however, a technocratic perspective on transitions of many policy makers and innovators. They believe that the innovation and its uptake need to be managed (protected) in the predevelopment phase and perhaps a little in the takeoff phase, but then the innovation will overcome all challenges on the basis of its technical superiority, and the transition will need no further management. As a result of this technocratic perspective, road maps dealing with the production of hydrogen pay no attention to the relevant actors and end-use practices, nor to the necessary coordination of efforts and actors to make widespread (worldwide) production, let alone use, of hydrogen possible. A transition, however, takes a lot of coordinated effort from many different actors, accurate timing, and management through all stages of a transition. Let us now first continue discussing the present and expected future distribution of hydrogen.

From Pipeline Transport to Distributed Facilities

At present, hydrogen is transported by pipeline or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail or barge. Pipelines are employed as an efficient means to supply customer needs but are limited to a few areas where large hydrogen refineries and chemical plants are concentrated. These pipelines are often owned and operated by merchant hydrogen producers. Hydrogen distribution via high-pressure cylinders and tube trailers currently has a range of 100–200 miles from the production or distribution facility. For longer-distance distribution of up to 1000 miles, hydrogen is usually transported as a liquid in superinsulated, cryogenic, over-the-road tankers, railcars, and barges and is then vaporized for use at the customer site.

In the future world, so the two DOE road maps envision, pipelines will distribute hydrogen to high-demand areas, and trucks and rail may distribute hydrogen to rural and other lower-demand areas. In time, distributed facilities will emerge in rural areas, and on-site hydrogen production and distribution facilities will be built where demand is high enough to sustain maintenance of the technology.

This future world sounds promising and fairly logical. But to create a demand that is high enough to sustain maintenance of the technology, the technology and the necessary infrastructure first have to be widely available. This "chicken and egg" or "demand and supply" issue, an issue that is typical for the second phase of a wide-scale transition, had not yet been tackled for the hydrogen transition but is also an issue that was addressed in the Hysociety project.

From Gas, Liquid, and Chemical Storage to Sorption-Based Storage Strategies for Transport Applications

On-board storage is an important issue for wide-scale application of hydrogen for transportation. The DOE road maps mentioned that today, hydrogen can be stored as a gas, as a liquid, or in a chemical compound in tanks and pipelines. Storage of gaseous hydrogen in tanks is considered to be the most mature technology but requires large volumes. Higher compression can increase the storage density but is still under development because it requires increased strength-to-weight ratio materials and structures. This process is in the product development phase. The DOE claims that liquid hydrogen storage is more space-efficient than hydrogen gas but requires cryogenic containers and is more energy-intensive. As a result, the liquefaction of hydrogen is accompanied with evaporative losses. This process is in the engineering development and early product development phases. Third, the DOE claims that hydrogen can be stored at high densities as reversible metal hydrides or adsorbed on carbon structures. Under certain temperature and pressure conditions, the hydrogen can be released from the material.

The DOE road maps claim that carbon nanotubes are a promising storage carbon material, at the moment. This process is in the laboratory research and development (R&D) and early engineering development phases. Chemical hydrides that can be stored in solution as an alkaline liquid are yet another alternative to direct hydrogen storage. According to the DOE road maps, this process is inherently safer than volatile or flammable fuel.

After the transition will have taken place, the DOE foresees that a selection of relatively lightweight, low-cost, and low-volume hydrogen storage devices will be available to meet a variety of energy needs. Pocket-sized containers will provide hydrogen for portable equipment, small and medium hydrogen containers will be available for vehicles and on-site power systems, and industrial-sized storage devices will be available for power parks and utility-scale systems. Solid state storage media that use metal hydrides will be in mass production as mature technology**[AuQ4]**, and mass production of storage media based on carbon structures will soon follow.

The most important challenge in the storage segment seems to be the upgrading of storage technologies and processes to the takeoff phase since most technologies and processes are still in the early predevelopment phase. Reducing storage density, lowering of cost of the full charging and decharging cycle, and increasing the energy efficiency of the storage option on a well-to-wheel basis are the next hurdles to be taken. Storage of hydrogen cuts across production, transport, delivery, and end-use issues, but these issues are not tackled integrally. In addition, the necessary changes on the regime level are not identified. What is necessary, for example, to get these early technologies out of the predevelopmental phase and niche level? With what kind of processes and what actors on the regime level do the current developers and the current technologies need to couple? What kind of accumulated learning processes are necessary for the takeoff phase of these technologies?

From Chemical Refining Applications to Widely Used Energy Carriers

The DOE road maps claim that at present, hydrogen is mainly used in chemical production as a feedstock, intermediate chemical and as a specialty chemical used in petroleum refining, metals treating, and electrical applications. Hydrogen has hardly any significant role as an energy carrier. Hydrogen is used as an energy carrier for aeronautic applications. However, the hydrogen that NASA uses constitutes only a small portion of total hydrogen consumption. Possible transportation applications include buses, trucks, passenger vehicles, and trains. Almost every major automaker has a hydrogen-fuelled vehicle program. The first "commercial" demonstrations are targeted between 2003 and 2006. Stationary power applications today include backup units, grid management, and power for remote locations, stand-alone power plants for towns and cities, distributed generation for buildings, and cogeneration.

The industry supplying hydrogen applications is still in its infancy. Most fuel cell systems installed to date operate on reformate from natural gas. Portable power generation today includes consumer electronics, business machinery, and recreational devices ranging from 25-W to 10-kW systems. Most of these portable units use methanol or hydrogen as fuel.

The DOE vision on hydrogen application is, however, that the presently infant hydrogen end application will be main end applications after the transition has taken place. The expectation is that the growth of distributed markets, small reformers, and electrolyzers will provide hydrogen for small fleets of fuel cell-powered vehicles and distributed power supplies. In the end, hydrogen will be available for every end-use energy need in the economy, including transportation, power generation, industrial process heaters, and portable power systems. It will be used in fuel cells for both stationary and mobile applications, and it will be used in portable devices. According to the DOE, in several years' time, hydrogen will be the dominant fuel for government and commercial vehicle fleets.

THE POTENTIAL OF A TRANSITION TO A HYDROGEN-BASED SOCIETY: HOW TO ASSESS CHALLENGES

Analyzing a Transition to a Hydrogen-Based Energy Supply

As mentioned earlier, a transition is a gradual and lengthy process of change in which the technical, infrastructural, ecological, economic, judicial, cultural, and political dimensions of a society or system interact and change fundamentally. This change occurs in four phases.

As briefly demonstrated in the previous section, the pervasive technocratic approach to a transition is doomed to fail. A transition involves many more than strictly technical aspects. The niche breakthrough of several radical or architectural hydrogen innovations, such as new conversion technologies, metal-hybrid storage technologies, and new fuel cell technologies, challenge existing technological conventions, regulatory frameworks, and established relations between consumers and producers. In addition, these new technologies and processes need to couple with and will in turn cause changes in the various dimensions. It is therefore important to assess the present state of the different dimensions that will surround the use of hydrogen. And it is also imperative to assess the gaps between the present and the future expected world in which the transition to widespread use of hydrogen has occurred.

In addition, managing all phases of the transition is necessary if one wishes to enhance the potential of a successful transition to a hydrogen-based society. If the transition management would only focus on the predevelopment phase and push the innovation to reach the takeoff phase in the expectation that technological superiority alone is a sufficient guarantee for success, the transition is most likely to end there. The innovation needs to be pulled, managed from the predevelopment phase into the second phase.

Only by examining what is taken for granted in the future as depicted in road maps is one able to define the actors, actions, and timing for changes that are necessary to make the future world realizable. This was, in essence, the task of the Hysociety project work package 1.

Assessing Challenges to a Hydrogen Transition: Developing a Methodology

Since Hysociety is an accompanying measure, the focus of the methodology was on the present situation in demonstrations, both at the scientific knowledge level and at the cultural, economic, political, institutional, and technological development levels. It was necessary to consider the results of current demonstration programs and the next steps needed to achieve market entry of hydrogen for both stationary and transport applications. These targets have been achieved by a methodology developed by the Policy Studies department of the Energy Research Centre of the Netherlands (ECN) that allowed for an evaluation of the present activities in hydrogen to assess the nontechnical barriers that existed for the introduction of hydrogen as an energy carrier. This identification included all relevant segments and all possible energetic uses of hydrogen. The scope of this article does not allow for an in-depth discussion of the methodology. For a detailed discussion we refer to the final report of the Hysociety consortium, available from the Hysociety Web page.

Because of the high number of partners, it was necessary to develop a methodology that made it possible to construct a database that in turn could be used for an analysis of hydrogen-related aspects at a European level. The methodology further prevented a technology-oriented description that would lack an in-depth understanding of sociocultural, political, judicial, cultural, and geographical aspects relevant to the use of hydrogen. This "whole system" approach highlighted the complex dependencies among the diverse system components and allowed for an assessment of the gaps between existing practice and the future expected world, a world in which the transition to widespread use of hydrogen has occurred. Cross-cutting and system-level issues and concerns received close attention.

The methodology focused particularly on all transition phases and on the different relevant dimensions: technological, infrastructural, political, institutional, cultural, economic, ecological, and geographical. The methodology also explicitly focused on the relevant actors and actions needed to overcome the challenges

Identifying Ongoing R&D and Demonstration Projects and Programs

At first instance it was believed that identifying only demonstration projects would provide a sufficient basis for analysis. However, being too rigid in the selection of the programs, *i.e.*, eliminating the ones that did not have demonstration elements, could lead to neglecting important items. In addition, some countries did not feature demonstration projects, and that would then automatically lead to the exclusion of these countries in the action plan to be developed. However, for the in-depth analysis of challenges and changes, only demonstration projects would be analyzed since these projects were expected to face most nontechnical challenges. It was agreed to have two categories of projects: demonstration projects (and projects related to the broader aspects of hydrogen) and other projects (which may include R&D projects, network projects, or feasibility projects). The first category was worthy of the "full treatment," whereas the second category required only a table to be filled out. The focus was on ongoing or very recently finished projects and programs to be certain that the identified projects represented the state of the art in hydrogen-related research, development, and demonstration. The identification of the projects was specifically aimed at providing a thorough basis for the analysis of obstacles and opportunities to the introduction of hydrogen.

Analyzing Challenges, Necessary Changes, and Required Actors

Some partners identified over 50 projects, while others were only able to identify three ongoing projects in their countries. In the selection of projects to continue with, several issues played a role. It was necessary to divide the workload evenly in the sense that every partner would have approximately the same amount of projects to analyze. The selection was a good representation of the possible and promising pathways (combination of technology chain segments). This representation further included different sources and technologies for conversion to hydrogen, different distribution and storage options, different conversion options of hydrogen, and finally, different end uses of hydrogen. The representation also covered as wide a number of segments of the technology chain. The representation included projects with a different focus (regional, national, and international), different funding sources, and different participants. Furthermore, the representation included projects with a high rating of the state of the art of the technologies used and included projects that were faced with as many challenges (preferably nontechnological) as possible. Last, it was decided to conduct the analysis with projects that were finished, had sufficient documentation, and showed no problems with accessibility to that information.

Taking into account all these requirements, it was decided that each partner would make an in-depth analysis of 15 challenges for each project. The analysis needed to be thorough and sound in the sense that the relevant community should acknowledge the results of the analysis as correct fact. To accomplish this, it was proposed to conduct a series of interviews with the project leaders and key actors of the projects under analysis.

Each segment (production, distribution, storage, conversion, and end use) is accompanied by different actors, and these actors can impede or facilitate the widespread introduction of hydrogen. One of first elements that needed to be identified once the major challenge and change were identified was the actor that would need to play a role in taking the hurdles ahead. But not only was it necessary to identify possibly important actors, it was also important to establish their standpoint toward a challenge or a change: Will the actor support, oppose, or do nothing?

Typically, this position is identified as being either positive or negative. It was proposed to also include yet another possible standpoint: neutrality of an actor. In principle, it is possible that actors, who might be potentially influential in the introduction of hydrogen, have a neutral position toward the introduction simply because they are not involved yet or do not exist yet. Sometimes a new kind of institution, for example, a monitoring institution, has to be established to fulfill a very specific and new action, or an existing actor needs to change competencies to accomplish the task deemed necessary to facilitate the introduction of hydrogen. Once the standpoint of actors is identified, the next step is to ascertain what the respective strength of the actor is. Does an actor that in principle opposes a change actually have the necessary power to oppose the change? Once the position and power of an actor is established, it is easier to formulate an action plan with respect to actions that need to be undertaken in the field of motivating, involving, or neutralizing potentially influential actors.

It is no easy task to transform information that is typically available in a qualitative way into a quantitative one. The definition of a rating system is an important requirement, but very often, this issue is not addressed properly. The main problem is that experts can classify similar conditions in very different ways and/or give the same score to very different conditions. This would make any further evaluation of the information really hard and would lower the reliability of such results. It was deemed relevant to quantify (rate) four elements: (1) the state of the art of a project; (2) the impeding strength of a challenge on the introduction of hydrogen; (3) the influence of an action on the implementation or transition of hydrogen; and (4) the likelihood that a change would take place. The sum of these ratings made it possible to derive a transition potential per country, per segment, per dimension, and per pathway. For each of the rated elements a classification based on five classes was agreed upon. In order to reduce deviations, the rating was accompanied by a rating index that secured a harmonization of the rating procedure.

Establishing a Database

An additional goal of work package 1 of the Hysociety project was to constitute a database with the data collected in different countries. This database would provide a quantitative global picture of the challenges, changes, dimensions, segments, and actors relevant to the introduction of hydrogen. This database provided the basis for a quantitative analysis of the following key issues for an action plan:

- an overview of the seriousness of economic, political, infrastructural, sociocultural, technological, geographical, and ecological challenges and the segments within which they occurred
- an overview of the relationship between specific kinds of challenges and the actors necessary to undertake actions
- key actors and marginal actors in different pathways
- insight into country-specific challenges and changes and boundary crossing challenges and changes.

SOME RESULTS

In the following section, some results of work package 1 of the Hysociety project are discussed. Because the scope of this article does not allow for an extensive discussion of the results, we refer to the final report available from the Hysociety Web site.

In the production segment, most of the challenges identified were technological and economic. In the distribution segment the challenges were mostly infrastructural, technological, economic, and sociocultural. In the storage segment the most frequent challenges were technological, economic, infrastructural, political, and sociocultural. The conversion segments recorded the most challenges in the technological, economic, and infrastructural dimensions, whereas in the end-use segment, most challenges were noted in the technological, sociocultural, and economic dimensions.

An analysis of the transition potential per dimension shows that all dimensions, with the exception of the economic dimension, have a transition potential just above 10, which is fairly good. The economic dimension is troublesome. Economic challenges occur in all segments, but most economic challenges occurred in the end-use (56 times) and production segments (38 times). The distribution segment raised 23 economic challenges, the storage segment raised 21, and the conversion segment raised 24. The transition potential per segment shows that the production, distribution, and storage segments have a lower transition potential than the conversion and end-use segments, but all segments show sufficient potential to overcome the challenges.

On the basis of the projects analyzed, the partners identified industry, the national government, and R&D as the most important actors for tackling the challenges identified in all segments. The international government was attributed a minor role in tackling the problems. If we relate this outcome to the analysis of the kinds of challenges most often found, the outcome is not surprising. The technological and economic challenges were the ones most often identified, and the production, distribution, and storage segments had the lowest transition potentials. To a lesser extent, the infrastructural, political, and sociocultural challenges were identified, and the end-use segment had a medium transition potential. It is therefore not surprising that R&D and industry were mentioned most often as important actors, and to a slightly lesser extent, the national government.

The partners identified the economic, technological, infrastructural, political, and sociocultural challenges as the most serious ones impeding the successful transition to hydrogen as a widespread energy carrier. Partners further identified the production, storage, and distribution segments as the most troublesome. For all these dimensions and segments the partners identified the same actors as being the most important in tackling the problems: industry, the national government, and R&D. The international government was attributed a minor role in tackling the problems.

The majority of influential R&D projects involved in the introduction of hydrogen as an energy carrier are supportive of change. There are almost no R&D projects that are in opposition to the identified necessary changes. The opposition in R&D projects occurs only in the end-use segment. The majority of influential industry involved in the introduction of hydrogen as an energy carrier (a broader category than simply R&D) is supportive of changes. There is almost no industry in opposition to the identified necessary changes. The opposition of industry is mainly in the production and end-use segments. The majority of influential national governments involved in the introduction of hydrogen as an energy carrier are supportive of changes. The national governments have almost no opposition to the identified necessary changes. There is, however, also a high number of influential national governments that are neutral to the changes. The opposition of national governments is especially noticeable in the production and storage segments. In addition, on the basis of the results of the demonstration projects analyzed, it can be concluded that only the influential international government will pose no problem to the introduction of hydrogen.

The majority of most other groups of actors were identified as supportive of changes. Finally, the influential public opinion of end users/consumers involved in the introduction of hydrogen is mainly in opposition to change. The highest opposition of influential public opinion occurs in the end-use segment. But public opinion is opposing changes in all segments, except for the distribution segment. In that segment, there is no opposition of public opinion according to the results of the analysis. However, the number of consumers and end users that are neutral, or that have not yet positioned themselves, is so high that if all became supportive, there would be approximately as many consumers in favor of as opposed to the necessary changes. In the segments production, distribution, storage, and conversion, most consumers are opposed to the changes. In the end-use segment, however, an almost equal number of consumers are opposed and supportive of the changes, while an even higher number of consumers are still neutral.

In all the segments, for approximately half of the required changes, no specific dates have been identified. The reasons could be either a lack of knowledge of the required date for change or a perception that there is no pressing need to undertake the actions to solve the problems. For all segments, except production, the majority of the changes have to take place before 2010. In the production segment the majority of the changes have to take place before 2006. For similar reasons, no specific dates have been identified for changes in all of the dimensions. In terms of the dates identified for the economic changes, the majority of the changes need to be addressed before 2007. The majority of geographical changes that are required should be addressed before 2006. The results indicate that the majority of infrastructural changes need to be addressed before 2010. Most of the required political changes need to be addressed before 2006 and sociocultural changes before 2007. The analyses reveal that for both ecological and technological changes the majority of those identified should be addressed before 2010.

CONCLUSION

To analyze transition potential of the introduction of hydrogen in different countries and on a general European level, a methodology was developed. This methodology focused particularly on all transition phases and on the different relevant dimensions: technological, infrastructural, political, institutional, cultural, economic, ecological, and geographical. The methodology also explicitly focused on the relevant actors and actions needed to overcome the challenges. The methodology prevented a technology-oriented description that would lack an in-depth understanding of sociocultural, political, judicial, cultural, and geographical aspects relevant to the use of hydrogen. This "whole system" approach highlighted the complex dependencies among the diverse system components and allowed for an assessment of the gaps between the existing practice and the future expected world, a world in which the transition to widespread use of hydrogen has occurred. More specifically, the methodology made visible what (technological and nontechnological) challenges are facing the introduction of hydrogen, what actions are necessary to overcome the challenges, who needs to undertake these actions, and if these necessary actors are willing and able to undertake the work.

Results of work package 1 of the Hysociety project indicate that a transition to a hydrogen-based economy still faces challenges in all segments (production, distribution, storage, conversion, and end use). Specifically, the cost of building a new hydrogen infrastructure is a major issue**[AuQ5]**.

After this detailed analysis and after the ratings have been analyzed, a road map needs to be formulated that tells the European Commission what pathway-a combination or a follow-up of pathways-is most robust in the near future in the sense that challenges for each dimension and each segment of the technological chain have been identified, necessary changes for each challenge have been identified, and the critical moment for each change and the key actors to manage each change are known. At present, many projects and activities are organized to create just such a coordinated effort to identify the most robust (combination) of pathways in the near future. As a result of activities such as the Hysociety project as well as the FP6 project Hyways, the International Partnership on the Hydrogen Economy, and the Hydrogen and Fuel Cell Technology High Level Platform the hurdles resisting the hydrogen economy can be tackled more efficiently.

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