Hydrogen Transport Economy for the North Sea Region

DEVELOPMENT OF A MODEL TO INCREASE THE SUSTAINABLE AND ECONOMICAL USE OF GREEN HYDROGEN PRODUCTION AND DISTRIBUTION

European Union The European Regional Development Fund

The Interreg IVB North Sea Region Programme

Investing in the future by working together for a sustainable and competitive region

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Europäisches Institut für Innovation

HyTrEc
Hydrogen Transport Economy
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Glossary

°C	Degree centigrade
CGH_2	Compressed Gaseous Hydrogen
CH_4	Methane
CHP	Combined Heat and Power
COM (2001) 547	Communication (2001) 547
CO_2	Carbon Dioxide
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EC	European Commission
EIHP	European Integrated Hydrogen Project
EQHHPP	Euro-Quebec Hydro-Hydrogen Pilot Project
EU	European Union
FCH JU	The Fuel Cells and Hydrogen Joint Undertaking
FCH 2 JU	The Fuel Cells and Hydrogen 2 Joint Undertaking
HFP	The Hydrogen and Fuel Cell Technology Platform
HyNet	Hydrogen Network
H	Hour
IHS	Information Handling Services
IP	Implementation Plan
kg	Kilogram
Km	Kilometre
kW	Kilowatt
l	Litre
LH_2	Liquid hydrogen
MW	Megawatt
NIP	National Innovation Programme for Hydrogen and Fuel Cell Technology
Nm^3	Standard cubic meter
N_2O	Nitrous oxide
PEM	Proton Exchange Membrane
PPP	Public Private Partnership
TÜV	German Technischer Überwachungsverein (Technical Control Agency)
U.S.	United States of America
µm	Micrometre

Abstract

The present thesis illustrates the development of a model to increase the sustainable and economical use of green hydrogen production and distribution. The research question is whether, and if so, in what extent the development of a model can increase the sustainable and economical use of green hydrogen production and distribution. First of all, it defines the importance of green hydrogen. Secondly, a range of production methods as well as the policy framework for green hydrogen is shown. Thirdly, a selection of initiatives and policy papers which promote green hydrogen follows. However, the sustainability model will be a compendium that lists necessary steps and actions which should be taken when developing and implementing a hydrogen infrastructure. Furthermore the model will focus on the use of sustainably generated hydrogen in the transport sector. Therefore, a short overview and comparison of the production cost and retail price of (green) hydrogen follows. This is followed by an insight of hydrogen transportation and its distribution as well as its application areas and stakeholders. At the end of the evaluation process there will be a proposal for an action plan with recommendations based on the outcome of the evaluation which should help to make a decision in favour of or against the establishment of a green hydrogen infrastructure. As part of the action plan, a policy cycle has been used to coordinate new policy implementation. The main cognition of this thesis shows that the first step of the policy development needs to be the implementation of a specific support for hydrogen and in a second step it needs to adopt hydrogen into the existing support for sustainability. Nevertheless, the outcome of this thesis comes to the conclusion that the development of such a model can contribute to increase the sustainable and economical implementation of production of green hydrogen and distribution.

1 Introduction

1.1 Initial situation

> *"The two most common elements in the universe are hydrogen and stupidity."* (Armaroli & Balzani, 2011, p. 279)

The quote mentioned above is from Harlan Ellison, an American author and detractor. In recent years, hydrogen has been announced to be the optimal technological solution for a clean and sustainable world economy (Momirlan & Vezirgolu, 2004, p. 30). Hydrogen, as quote above states, is the most common element in the universe. Hence, the environmental and energy problems of our planet would have been solved, if the development of a sustainable hydrogen technology could immediately replace the fossil fuel technology. However, the contradiction between the elements stupidity and hydrogen is that although hydrogen is the most common element, its potential has not been used so far (Züttel, et al., 2008).

According to current scientific research, the emission of greenhouse gases causes an anthropogenic climate change. Based on this background, greenhouse gas emissions should already be avoided or reduced in all approaches. The reduction of greenhouse gas emissions is also sought in the production of hydrogen. Unfortunately, molecular hydrogen does not exist on our planet. Hydrogen in nature is mainly combined with other elements such as water. To be able to use hydrogen, it has to be produced by using energy (e.g. electrolysis), ensuing from hydrogen rich compounds.

Hence, hydrogen is not classified as an alternative fuel, rather as an energy carrier (Armaroli & Balzani, 2011, p. 279). The energy carrier can be produced from renewable energy sources without any CO2 emissions, it can be grid-bound transported; and it is possible to store it. Current applications of hydrogen are realized in the chemical industry and will increasingly be seen in the transport sector and also for storage of renewable energy (e.g. electricity from wind). For either mobile and stationary applications it is proven that hydrogen produced out of renewables is associated with significantly lower greenhouse gas emissions than conventionally produced hydrogen (e.g. Natural gas or Coal) (Armaroli & Balzani, 2011, p. 281)

The energy concept of the German Federal Government, for example, provides a clear plan for the expansion of the share of renewable energies in electricity consumption from the current 25 percent (Bundesverband der Deutschen Energie- und Wasserwirtschaft, 2014) to 80 percent in 2050 (Umwelt Bundesamt, 2013). The prerequisite for the utilization of renewable energy is an efficient electricity grid that can absorb power fluctuations. For example, off shore wind turbines produce more power at certain intervals, than is needed at the time. In the UK, renewables produce 7% of the UK's electricity. The EU targets mean that this is likely to increase to 30% by 2020. From 2020, renewable energy will continue to be an important part of the strategy to reduce carbon emissions. To achieve this, a range of technologies will need to be used, such as onshore and offshore wind farms, biomass power stations or hydropower systems (Energy UK, 2014). Further, the proportion of electricity generated from renewable sources in Sweden is about 60%, in Denmark close to 40% and Belgium about 10% of gross electricity consumption (Eurostat, 2012).

In order not to waste energy, it must be stored. One way to store electricity may be realized via the path of hydrogen production (Deutscher Wasserstoff- und Brennstoffzellen- Verband, 2004). Economic development and prosperity together with the concern for the local and global environment are high on the national, European and worldwide political agenda. Therefore a safe and increasingly clean energy supply for industry, mobility and the private sector is needed. At the same time knowledge-intensive industries need to be stimulated, which form a reliable basis for global competition for skills as well as jobs for the future (European Technology Platform for Hydrogen and Fuel Cells, 2007, p. 2). The hydrogen energy and the use of fuel cells can contribute significantly to achieve these goals.

It has become clear if hydrogen is produced economically and environmentally efficiently, it will be an energy option for the future. Based on that, targeted support and promotion of the emerging hydrogen and fuel cell industry is established in several programs for research and development as well as industrial initiatives and activities. This could create a great opportunity to positively influence this process and accelerate the development of the market.

1.1 Presentation of the problem

Currently 96% of the world's hydrogen is generated from hydrocarbon sources such as the reforming of natural gas or oil/naphtha and coal gasification (Armaroli & Balzani, 2011, p. 281). The CO_2 emissions of this production are still relatively high. Thus a clean and sustainable way to produce hydrogen is needed. The energy carrier hydrogen and the use of fuel cells can contribute significantly to achieve the national European and worldwide objectives, especially in the areas of energy security, air quality; reduction of greenhouse gas emissions (Kyoto protocol) and industrial competitiveness. It can be attractive as well as competitive if there is a political environment that stimulates research, development and distribution. If the economy is set into the right position it will achieve and strengthen these essential benefits for the community over time (Armaroli & Balzani, 2011, p. 279).

Traffic applications play a crucial role, since the development of fuel cell motors for vehicles. This is a major driver of the overall development (Europäische Technologieplattform Wasserstoff und Brennstoffzellen, 2007, p. 5). Initially, special markets including those for specialized vehicles (e.g. forklifts) and portable devices started in 2010. Additionally, stationary applications will reach a broad market establishment by 2015 and transport services to the mass market by 2020 (Garche, 2014)

At the European level, there is mainly one milestone as of today: The Hydrogen and Fuel Cell Technology Platform (HFP) established an Implementation-Plan (IP) in 2006 to target 10-20% of sustainable hydrogen production by 2015 (backed by Industry) (European Technology Platform for Hydrogen and Fuel Cells, 2007, p. 25). Furthermore the IP target has not considered influence of policy. Nevertheless, several national hydrogen and fuel cell platforms emerged with, in some cases, proposed sustainable targets. Although some targets are proposed, the implementation speed of the development of green hydrogen is based on two parameters, on technological progress and on political support. Taken into account the political conditions for building up production capacity and infrastructure (distribution) of green hydrogen as well as the replacement and implementation of hydrogen vehicles, it seems the market integration of green hydrogen is a chicken-egg-dilemma. Thus, it is time to act with urgency.

1.2 Objectives and Methodical approach

The research question of this thesis should clarify whether, and if so, in what extent the development of a model can increase the sustainable and economical use of green hydrogen production and distribution. Currently, hydrogen policy is primarily focused to use hydrogen generated from natural gas, coal or liquid hydrocarbons. In this regard, it is important to have a compilation of policy recommendations as well as cost and production information regarding renewable energies. For this purpose it is the goal of this paper to describe a sustainability model which helps the partners and all other interested stakeholders to display the production and distribution of green hydrogen in their region. Thus the model will be a guideline which shall help the regions and authorities to plan and to develop a green and sustainable hydrogen infrastructure to assess their conditions, chances, threats and opportunities regarding the implementation of a hydrogen infrastructure.

However this model is not a planning tool in a classical sense. First, it defines the importance of green hydrogen. Second, a range of production methods as well as the policy framework for green hydrogen is shown. Third, a selection of initiatives and policy papers which promote green hydrogen follows. However, the sustainability model will be a compendium that lists necessary steps and actions which should be taken when developing and implementing a hydrogen infrastructure. By doing so additional examples of previous projects will be illustrated. Furthermore the model will focus on the use of sustainably generated hydrogen in the transport sector. Therefore, a short overview and comparison of the production cost and retail price of (green) hydrogen follows. This is followed by an insight of hydrogen transportation and its distribution as well as its application areas and stakeholders. At the end of the evaluation process there will be a proposal for an action plan with recommendations based on the outcome of the evaluation which should help to make a decision in favour of or against the establishment of a green hydrogen infrastructure. While this paper gives a broader overview, detailed models are in use that allows scenario planning based on a wide range of costs and benefits and sensitivities e.g. electricity prices. Thus, the outcome of this paper should help the detailed models (e.g. the dynamic model for hydrogen vehicle and refuelling infrastructure deployment) developed for and by partners as part of HyTrEc.

The main requirements under which the evaluation process within this model will be conducted are economical, sustainability and competiveness. Due to the fact that such a model simplifies and speeds up planning and decision making processes it can be the basis of a policy initiative. This initiative will identify the best means of using hydrogen as an energy vector to link sustainable energy with transport thus enhancing the part of green hydrogen (produced from renewable sources) vs. brown hydrogen (produced from hydrocarbon sources) in an energy mix. This model will also be used to promote policy support at the EU level for the integrating and use of renewable energy (focus on wind energy) for hydrogen production. Further, designations of necessary steps towards the establishment of water electrolysis as the most important element of a hydrogen energy economy are shown.

2 Green hydrogen

2.1 What is green hydrogen

As it is mentioned before, most of the world's hydrogen is produced from fossil fuels, so called brown hydrogen, in different kind of processes which generate, next to hydrogen, carbon dioxide (CO_2) (Rifkin, 2003)The cheapest and most common way today to produce brown hydrogen is the extraction of hydrogen from steam reforming of methane (CH_4). As the following overall reaction shows, this method to produce hydrogen emits CO_2; hence the carbon footprint of brown hydrogen is negative.

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \qquad [2.1]$$

The European standard defines requirements for the production (generation) of green hydrogen for energy or material use. According to the present standard certified hydrogen is referred to as green hydrogen. Therefore the carbon footprint of its production has to be neutral or positive. One way to produce green hydrogen is the electrolysis of water in combination with renewable energies (e.g. photovoltaic, hydropower or wind). Only an insignificant quantity of about 4 % of the world's hydrogen is produce by this method (Figure 2). Due to a high demand of electricity, the electrolysis has much higher production costs then all of the other methods (Table 1). Nowadays, hydrogen produced by electrolysis is only used when high-purity hydrogen is needed, for example for fuelling fuel cells in transport modes. Thus, as the following overall reaction shows, electrolysis is CO_2 neutral but electric energy consuming.

$$H_2O + \text{electric energy} \rightarrow H_2 + \tfrac{1}{2}O_2 \qquad [2.2]$$

2.2 Definition of Green Hydrogen in the Clean Energy Partnership (CEP)

1. Green hydrogen is produced from electrolysis using electricity from renewable energy sources according to the Electricity Criteria for Green Hydrogen (see point 2.2.2), or
2. Hydrogen from biomass produced in a certified green thermochemical or biological conversion process. Proof is to be furnished that the process of producing hydrogen from biomass causes fewer CO2 emissions than the production of hydrogen from natural gas reforming. The following certificates are recognised:
   - TÜV SÜD 'Green Hydrogen' certificate (see point 2.4).
3. Other certificates may also be considered.
   - Hydrogen as a by-product of chemical processes per se is not considered green hydrogen. An exception is made if the hydrogen by-product is replaced with certified biogas according to the substitutions/allocations process. (Clean Energy Partnership, n.d.)

2.2.1 Basis of calculation

The manufacturing process is the key to the definition of green hydrogen. The compression/liquefaction, transportation, or the supply of hydrogen for cars and buses at the filling stations are not considered. (Clean Energy Partnership, n.d.)

2.2.2 Electricity criteria for green hydrogen

1. The electricity provided for the hydrogen electrolysis is produced exclusively from 100% renewable energy. Below are the generally accepted energy sources and technologies that are defined as renewable in German legislation for the purposes of the Renewable Energy Law (EEG). They are hydropower, wind power, solar radiation, geothermal, biomass, landfill gas, gas from purification plants, and mine gas. The latter, however, is not accepted in the project as a renewable energy source.

2. Electricity supplied as a renewable energy can be traced back to clearly described and identifiable sources. The supplier shall openly disclose these sources to customers and other interested parties in an appropriate form [e.g. on the internet]. As long as this is guaranteed, certificates can also be considered in verifying the energy sources.
3. The following certificates are recognised:
    - Renewable Energy Certificate System (RECS)
    - European Energy Certificate System – Guarantee of Origin (EECS-GoO)
4. Physical direct or swap contracts can be considered.
5. If certificates are used in accordance with point 3, the following requirements regarding the age of the plant apply:
    - At least a third of the electricity sold should be generated in newly built renewable energy power plants that are not more than six years old,
    - At least a third of the electricity sold should be generated in renewable energy power plants that are not more than twelve years old.

    When using of physical direct or swap contracts, there are no requirements regarding the age of the plant.

6. The energy balance for supplying the green electricity product must be equalised within one year (chronologically balanced supply). The provider uses a reliable method to continuously monitor and safeguard the balance between production/purchase and provision/supply.
7. Electricity for the hydrogen electrolysis must be certified by one of the following labels:
    - TÜV-Nord Ökostrom,
    - TÜV-Süd Ökostrom,
    - Grüner Strom Label,
    - OK Power.

Further criteria for certified green electricity from hydrogen may also be considered, including certificates that are currently in development. (Clean Energy Partnership, n.d.)

2.3 Power to hydrogen - production methods and sustainability of green hydrogen

Due to the strong expansion of renewable energy, water electrolysis is gaining an increasing importance as a method of production of so-called power-to-hydrogen. With hydrogen as an energy storage device the continuation of electricity from renewable energy sources is promoted, especially wind power and photovoltaic. Thus, water electrolysis is able to utilize the production peaks from these renewable energy sources to supply the gas grid either directly in the form of hydrogen or after subsequent methanation as methane. The following figure shows a simplified layout of green hydrogen production, storage and use cycle which demonstrates the ways green hydrogen in combination of renewables is created, stored, distributed and used as a fuel.

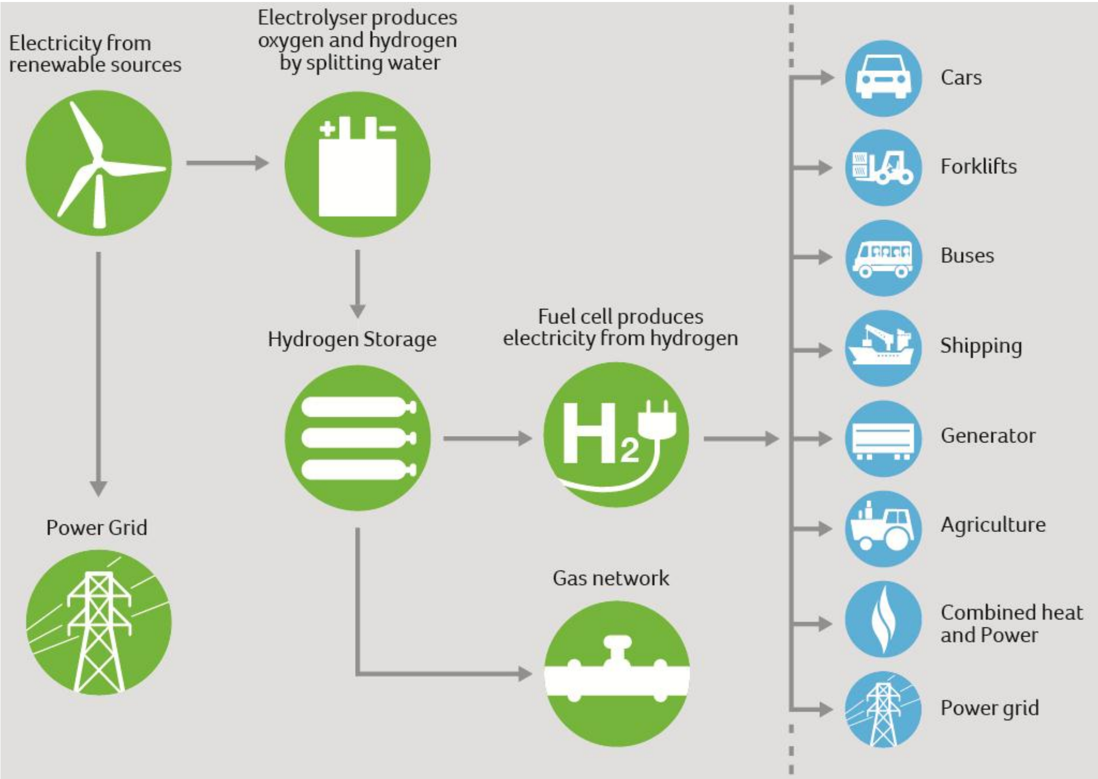

Figure 1: Production, distribution, storage and use cycle of green hydrogen (Source: Author's illustration based on HyTrEc partnership; a hydrogen strategy framework for Aberdeen City Region)

In 2012, the global annual production of hydrogen was estimated at 55 million tons, which equals to less than 3% of the world's primary energy demand (Kalamaras & Efstathiou, 2012). Over the past five years the consumption of hydrogen increased by roughly 6% per year (Kalamaras & Efstathiou, 2012). To be able to classify this increase it is auxiliary to compare with one of the main fossil energy sources. In 2013, the global amount of oil production was 4185.1 million tons. This implies, compared with 2012 the global oil consumption raised by 1.4% (British Petroleum, 2014). Thus, the increase of hydrogen consumption is in comparison to the global oil consumption more than three times higher.

In calculation of the greenhouse gas emissions of green hydrogen, preparation of the input materials and the supply of hydrogen are included with the first buyer. Sustainability may be defined in this area in terms of cost-competitiveness, low in well-to-tank carbon content, high in energy efficiency and a minimal dependence on fossil fuels.

2.3.1 Water electrolysis

However, as the following figure shows hydrogen is mainly used as a crude material in the chemical and petrochemical industries, to produce primarily ammonia, purified (refined) fossil fuels by hydrocracking, as well as an assortment of chemicals. Although hydrogen has a great potential in the transport sector, its primary function is currently only in the aeronautic-industry as a fuel for rockets.

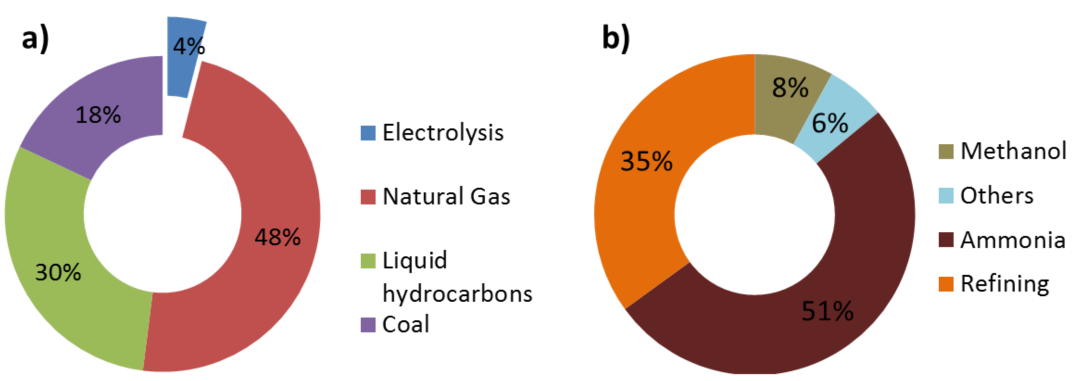

Figure 2 (a) Sources of hydrogen production worldwide. (b) The major hydrogen-consuming sectors in the world
(Source: Author's illustration based on (Armaroli & Balzani, 2011, p. 281))

Water electrolysis is considered to be the method with the greatest potential to produce green hydrogen. Since other production methods are cheaper, for example, based on petroleum, gas or coal, only 4% (Figure 2) of the global hydrogen is currently produced by electrolysis. Recently, due to low baseload electricity prices as a result of the raising amount of electricity produced by renewables (Mihm, 2013) the production of green hydrogen by electrolysis becomes more and more attractive. An additional boost for the electrolysis is the partial over-production of electricity generated by renewable energy.

2.3.1.1 General concept of an alkaline electrolysis

Water electrolysis means the decomposition of water into hydrogen and oxygen by using electrical power. The electrolysis of water consists of two reactions that occur at the two electrodes (cathode and anode spaces). The overall reaction of this redox reaction is listed in chapter 2.1 [chemical equation 2.2]. The following figure shows a standard application of an alkaline electrolysis.

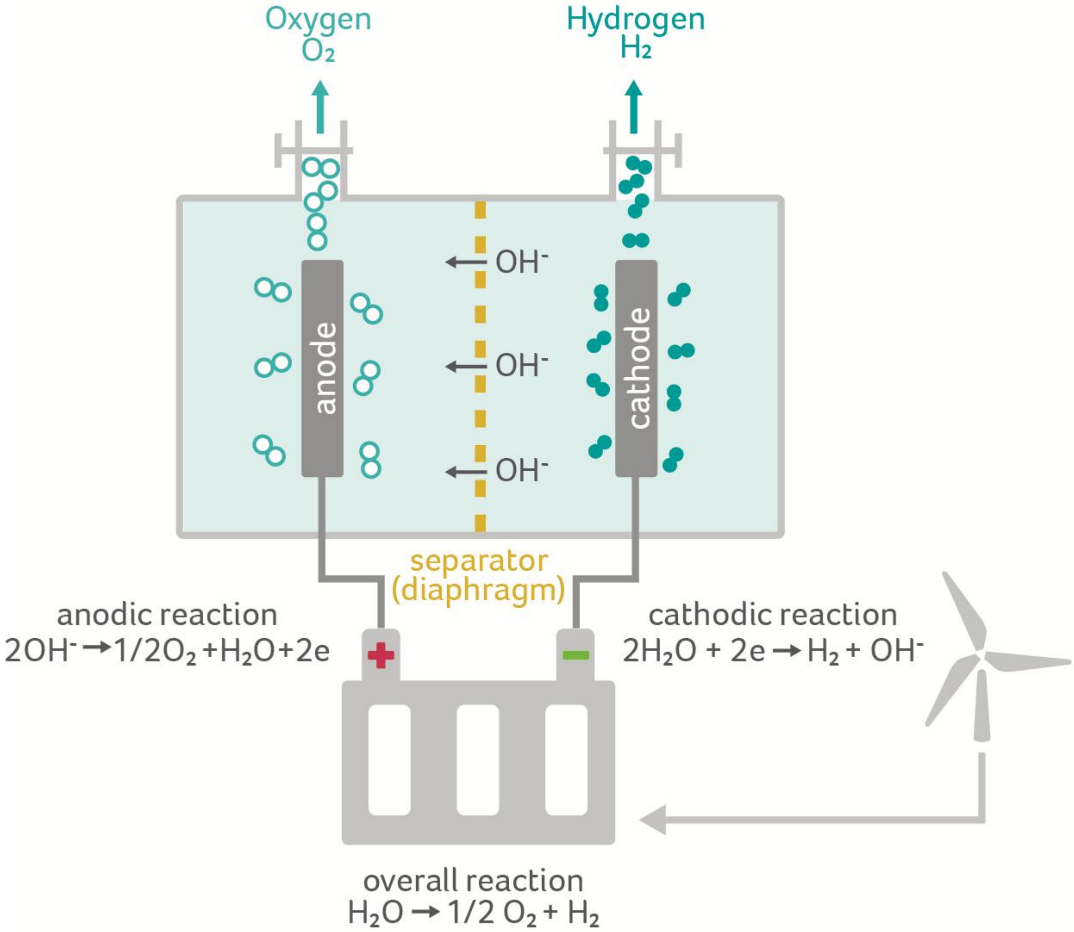

Figure 3: Application of an alkaline electrolysis
(Source: Author's illustration based on (DLR, 2012, p. 13)**)**

The technological conditions of the water electrolysis are promising. Nowadays, a standard commercial electrolyser has an efficiency of approximately 60-70%. In other words to produce 1 kilogram of (compressed) hydrogen approx. 50 kWh of electric power is needed (Armaroli & Balzani, 2011, p. 284). However, the electrolysis of 1 tonne of fresh water (ambient conditions) amount to 111.5 kg of hydrogen and 888.5 kg of oxygen. Nevertheless, if the electrolyser is modified and higher temperature or steam is used even better efficiency could be obtained. However, current industrial applications of hydrogen are quite insufficient. This is mainly due to the co-produced oxygen that is predominantly released into the atmosphere.

2.3.1.2 Proton exchange membrane electrolysis

In the race for the key technology in this margin are mainly two methods, alkaline (Section 2.2.1.1) and proton exchange membrane electrolysis (PEM) (Figure 4). The electrical efficiency of PEM electrolysis is about 40-60% (Tsiplakides, 2012). Nevertheless it is still significantly more expensive than the alkaline, also due to the noble metal catalysts. In the PEM electrolysis a very thin proton-conducting membrane (~180 µm) separates the areas in which oxygen and hydrogen are produced (Frauenhofer ISE, 2007, p. 70). In combination with a voltage source, platinum or rhodium electrodes (Anode and Cathode) are attached to both sides of the membrane.

Unlike alkaline, PEM electrolysers can be loaded with up to three times the value of their rated output. In addition to its high dynamics, PEM also has the advantage that it does not have to be maintained at a certain operating temperature. This means, if it is completely switched off it will not need preheating before switching on. Due to the infinitely variable operation from 0-100% load and a rapid response in the range of seconds to load requirements, this technique can be well coupled with renewable energies (DLR, 2012, p. 15). Despite a contemporary limited system size of about 100 kW, the prospects for an early market maturity are positive (DLR, 2012, p. 42).

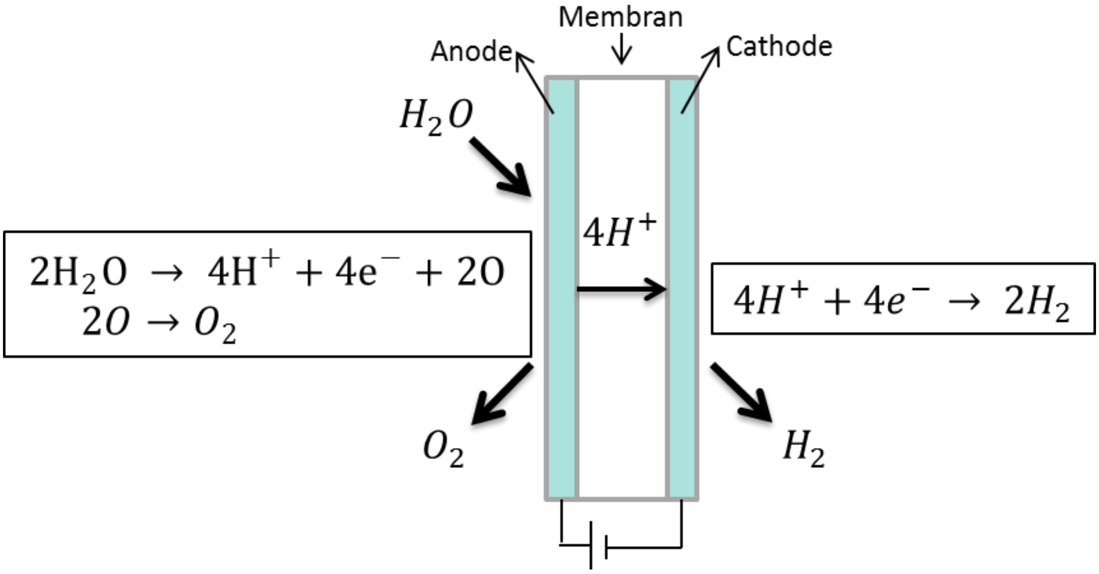

Figure 4: Polymer electrolyte membrane electrolysis
(Source: Author's illustration based on (DLR, 2012, p. 14)**)**

2.3.2 Biohydrogen

Another way to produce green hydrogen is to convert biomass into hydrogen by fermentation, gasification or pyrolysis. The latter two methods are mainly coupled with steam reforming. Due to different technologies and surrounding conditions, the efficiency of these methods varies from 50-80% (Erneuerbare Energien, 2010). According to the German Technischer Überwachungsverein (TÜV), who is an independent control agency responsible for technical security controls in the name of the government, steam-reforming of bio methane is considered as green hydrogen. The argument to promote steam-reforming of biomethane as green hydrogen is based on its greenhouse gas reduction potential of 35% compared to fossil fuels or brown hydrogen (TÜV SÜD Industrie Service GmbH, n.d.).

Due to the fact that burning biomass releases only as much CO_2 as the plant uses to grow, hydrogen production out of biomass is considered to be CO_2 neutral. Nevertheless, before the biomass is used, it has to be harvested, transported as well as transformed into an utilisable form whereby mainly fossil fuels are being used. Thus, the overall CO_2 footprint of biomass is negative and hereby in this paper not considered as green hydrogen.

Additionally, hydrogen produced biologically mainly by the photo-biological production is also considered as green hydrogen. This method to produce hydrogen uses algae that absorb sunlight. By influencing their operating photosynthesis, the separation of fresh water into hydrogen and oxygen is achieved. These processes are commonly titled biohydrogen. Because those biological processes consume than emit CO_2, its carbon footprint is positive. Although this method shows great potential, the cultivation of algae and bacteria is associated with high investment and operating costs. Additionally the photo-biological production of hydrogen has still a low commercial efficiency factor (5-10%), and therefore does not show any market maturity, yet (Bast, 2004). From this vantage point, this paper does not consider biohydrogen any further.

2.4 Policy framework for the production of green hydrogen

Currently there is no internationally recognized policy framework for the production and distribution of green hydrogen. Nevertheless, some countries have already developed their own national standards, for example Germany and the UK.

2.4.1 TÜV SÜD Standard CMS 70

The development of a certificate (Standard CMS 70) for green hydrogen in Germany was carried out by TÜV SÜD. According to this, the production of green hydrogen is limited to a certain level of greenhouse gas emissions and has to be compared with the current values of the emissions for conventional natural gas reforming (TÜV SÜD Industrie Service GmbH, 2011).

2.4.1.1 Scope of certification of green hydrogen

The TÜV SÜD Standard CMS 70 defines that green hydrogen can be granted if the hydrogen has a greenhouse gas reduction potential of at least 35 percent compared to fossil fuels and compared to conventional hydrogen. The greenhouse gas reduction potential for hydrogen from electrolysis of water is considered at a minimum of 75 percent. The standard (TÜV SÜD Standard CMS 70) defines criteria for the materials and energy used and the calculation of the greenhouse gas reduction potential for green hydrogen. For the calculation of greenhouse gas emissions carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) have to be considered. The gases are weighted as follows:

- Carbon dioxide (CO_2): 1 t CO_2 equivalent / t CO_2.
- Nitrous oxide (N_2O): 296 t CO_2 equivalent / t N_2O.
- Methane (CH_4): 23 t CO_2 equivalent / t CH_4.

An extension of the standard equivalent input materials and processes (e.g. gasification of hydrocarbon-containing waste and residual materials) is provided (TÜV SÜD Industrie Service GmbH, 2011, p. 4).

2.4.1.2 Requirements on green hydrogen

The production of green hydrogen can be traced back to well-defined, identifiable and quantifiable sources. The green hydrogen fulfils in terms of purity and ingredients such as N_2, O_2 and H_2O at least the quality requirements for hydrogen 3.0 (chemical purity ≥ 99.9%) (The Linde Group, 2014). Otherwise, those emissions must be added to the hydrogen which would be incurred during the preparation up to the quality level of hydrogen 3.0. In case of higher emissions to fulfil the quality requirements the real emissions must be calculated. (TÜV SÜD Industrie Service GmbH, 2011, p. 6)

2.4.1.3 Energy resources for the production of green hydrogen

In order to guarantee that the production of green hydrogen does not use electricity produced from fossil fuels, evidence of the use of electricity from renewable sources must be provided. Within the EU, the origin of the electricity must be proven according to the Renewable Energy Directive 2009/28/EC. The use of electricity from renewable sources can be accounted, if at least 30 percent of the provided power comes from new plants whose initial start-up into service is not later than 36 months after its initial certification. In this case, any kind of renewable power plant which is older than ten years after the commissioning, will no more be considered as a new plant for the purposes of this standard. Statutory funded electricity which receives a higher compensation per kilowatt hour fed into the grid will not be considered. (TÜV SÜD Industrie Service GmbH, 2011, p. 6)

2.4.2 Green Hydrogen Standard – DECC Requirements

The Department of Energy & Climate Change (DECC) works to make sure the UK has secure, clean, affordable energy supplies and promote international action to mitigate climate change. DECC is a ministerial department, supported by 8 agencies and public bodies. The DECC are currently working with the Scottish Hydrogen and Fuel Cell Association (SHFCA) on developing a green hydrogen standard, based on the following criteria (Department of Energy & Climate Change, 2014).

2.4.2.1 Industry Support

The Standard must be capable of receiving the backing of the majority of the industry.

1. Government interprets ‘industry’ in this case to refer to any company that produces or with meaningful plans to produce low carbon or renewable hydrogen, either for sale or for an intermediate purpose, and their representative organisations.
2. This does not exclude companies investing in innovation projects that are not expected to produce hydrogen at scale for a considerable period, such as pre-combustion CCS.
3. Government currently recognises the UK Hydrogen & Fuel Cell Association and the Scottish Hydrogen & Fuel Cell Association as the representative bodies of the industry, and the minimum backing level Government requires is the support of the standard by these organisations.

The Standard must be industry-led which means that the Government cannot currently commit any resources to the development and monitoring of this standard, and will require industry to deliver it.

2.4.2.2 Stakeholder Support

Ensuring that the Standard delivers and is seen to deliver a low carbon or renewable fuel source requires the backing of key stakeholders.

1. This may require the involvement of environmental NGOs at an early stage in the process to ensure buy-in.

The Standard will require the support of relevant Government departments and delivery organisations.

1. This includes Ofgem, the Department for Business, Innovation & Skills, the Department for Transport, the Office for Low Emission Vehicles, and the Department for the Environment, Food & Rural Affairs.
2. It is incumbent on DECC to secure this support.

2.4.2.3 Technology Neutrality

The Standard must not be designed in such a way as to exclude any means of producing low carbon hydrogen.

1. This may refer to any existing method, or any method that may be developed in the future.
2. DECC currently recognises the following methods of producing low carbon hydrogen and would expect any standard to apply to them all as a minimum: Electrolysis of water using low-carbon electricity;
   - Steam reformation of biomethane produced from appropriate feedstock's;
   - Steam reformation of natural gas or coal with CCS;
   - Thermolytic splitting of water using low-carbon heat;
   - High temperature electrolysis using low-carbon electricity.
3. Low carbon hydrogen produced as a by-product from industrial processes may be covered by the standard if it is shown to be capable of meeting the carbon intensity standard following a life cycle analysis of the process using an agreed methodology.
4. Nascent technologies should not be excluded from the standard if they are currently not capable of hitting the carbon intensity target but there is a clear and plausible plan for improving their performance within a five year timeframe.

2.4.2.4 Standard Administrator

There must be a body charged with administrating the Standard.

1. Government accepts that in the early years of the Standard and in the absence of a support mechanism for low carbon hydrogen such a body may be under resourced, and that processes for auditing and inspection of plant may be less rigorous.

2. However, Government would expect a clear pathway towards a robust process for verifying the Standard to be included in a plan for the Standard's development.

The body charged with administrating the Standard must be independent of any one company that has low carbon hydrogen production interests.

1. The body may be an adjunct of an industry association, a jointly owned subsidiary of at least five low carbon hydrogen production companies with varying technology interests, or a wholly independent entity.

The body must be empowered to share data with appropriate third parties, including DECC.

2.4.2.5 Registration of Plant

The standard must make provision for the registration and verification of low carbon hydrogen production plant.

1. Registration of plant must include details of the process by which the applicant intends to produce low carbon hydrogen. This may include schematic diagrams showing the process of production to distribution or another form of verification.
2. The amount of low carbon hydrogen the applicant expects to produce per year must be included in the application.
3. Applicants must be willing to accept inspection of their plant to verify the details of their registration, and must record any changes to its design or other factors that may impact on volume of production and submit them to the Standard Administrator.
4. Applicants producing hydrogen from biomethane or other biological sources should also be required to produce details of their feedstock and its supply chain to demonstrate compliance with sustainability standards.

2.4.2.6 Enabling a Market

The Standard must make provision for the trading of low carbon hydrogen.

1. This may take the form of enabling applicable low carbon hydrogen production facilities to issue certificates of origin guaranteeing the status of their product.
2. Any sort of certification or other form of trading enablement will be dependent upon registration with the Standard Administrator and must correspond with the stated annual volume of production.
3. Certificates of origin must be registered with the Standard Administrator for verification purposes.

The Standard must make provision for the trading of renewable hydrogen.

1. In addition to the above, while any form of renewable energy target or other legislation mandating renewable energy production is in force in the UK, the Standard must make provision for low carbon hydrogen produced from renewable sources to be certified as such.
2. Renewable energy is defined in line with the EU Renewable Energy Directive 2009.
3. Renewable hydrogen produced from high carbon sources such as biomass feedstocks with high lifecycle emissions should not be covered by the Standard.

2.5 Selected initiatives and policy papers promoting green hydrogen

The establishment of a hydrogen society does not only help to solve our dependency on fossil fuels but also helps to achieve various energy policy objectives. However, in Europe, for example, the EU Member States committed by 2020, to reduce the greenhouse gas emissions by at least 20% in comparison to the level of 1990 as well as to achieve a 20% share of renewable energy in overall energy consumption (Europäische Kommission, 2014). Taking this into account an international standard to increase the sustainable and economical production and distribution of green hydrogen is needed. The following section presents a selection of initiatives and policies which promote green hydrogen in one way or the other.

2.5.1 The Hydrogen and Fuel Cell Technology Platform - Implementation-Plan

In 2003, the European Commission launched the Hydrogen and Fuel Cell Technology Platform (HFP) which established in 2006 an Implementation-Plan (IP) to develop the use of hydrogen and fuel cells in Europe. The HFP is a public private partnership (PPP) that supports research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. Its main target is to encourage and promote the market introduction of hydrogen and fuel cell technologies. The first step of the HFP is to explore the technological as well as the market developments needed by 2020 to establish a hydrogen society by 2050. The IP concentrates mainly on the following four objectives (European Technology Platform for Hydrogen and Fuel Cells, 2007, p. 2 and 25):

- 10-20% of sustainable (green) hydrogen production by 2015 (backed by Industry)
- Establishment of a sustainable mobility through hydrogen vehicles and refuelling stations
- Establishment of an efficient, distributed and diversified energy production through the promotion of fuel cells for heat and power generation
- Promotion of commercial use of both hydrogen and fuel cells through the use of fuel cells for early markets

2.5.2 Fuel Cells and Hydrogen 2 Joint Undertaking

The Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) is a PPP backing research, technological development and demonstration activities in fuel cells and hydrogen technologies in Europe. Its objectives are to quicken the market introduction of hydrogen in Europe. In May 2014 the EU officially settled this PPP as part of the EU's new funding programme for research and innovation of the so called Horizon 2020. The second phase of the programme will continue to conduce to the targets of the FCH JU (part 1). According to this, its target is the development of a firm, sustainable and global fuel cells and hydrogen market in the EU. The financial support for this programme amounts 664 million Euros (backed by the industry and research partners) (Fuel Cells and Hydrogen Joint Undertaking, 2014, pp. 1-2)

2.5.3 National Innovation Program - Hydrogen and Fuel Cell technology

In order to ensure the further development of technologies, the German government, industry and science have jointly initiated in 2006, a strategic alliance called the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). The objective of the NIP is the market preparation of products and applications which are based on hydrogen and fuel cell technology. In addition, it is intended to accelerate the market preparation of hydrogen products decisively. Furthermore, Germany should become the leading market for sustainable mobility and energy supply. The NIP is divided into four program areas, transport and hydrogen infrastructure, stationary power supply, special markets and security of hydrogen supply. The total investment for the 10 year period of the NIP amounts to 1.4 billion euros. The total investment will be funded equally by the federal government and the participating industry (Bundesministerium für Verkehr und Infrastruktur, n.d.)

2.5.4 EU Directive and Commission Communication - COM (2001) 547

The COM (2001) 547 is a communication paper on the promotion of alternative fuels for the transport sector. The communication considers the necessity to shrink the dependency on fossil fuels as well as greenhouse gas emissions to meet the Kyoto agreements for the industrialized countries. It also complies with the expectations and needs of our transport sector. This includes an easy and extensive supply of alternative fuels (e.g. hydrogen or biofuels) as well as a sufficient availability of public and private transport. These targets can be achieved by replacing fossil fuels like diesel or petrol through the increase of alternative fuels in the transport sector by 2020, to an aggregate level of up to 23%. Accordingly, this includes the increase of green hydrogen use of up to 5% of the total energy requirements (Commission of the European Communities, 2001, p. 13).

2.5.5 List of additional European strategic projects to increase the use of green hydrogen production and distribution

Hereinafter other European projects are identified which were established to increase the application of green hydrogen and its distribution. It turns out that 20 years ago the first attempts already had been carried out to accelerate the introduction of green hydrogen.

- The Euro-Quebec Hydro-Hydrogen Pilot Project (EQHHPP) (1989-1999): The aim of this project was investigating the production, distribution and end applications of green hydrogen (Gretz, 1998).
- The European Integrated Hydrogen Project (EIHP) (1998-2004): The target of this project was a basic development of essential legislation for the sustainable approval of compressed gaseous hydrogen (CGH_2) and liquid hydrogen (LH_2) vehicles and refuelling infrastructures in Europe (European Integrated Hydrogen Project, 2004).
- The hydrogen network (HyNet) (2001-2004): The main tasks of the project were the development of a European roadmap for a sustainable hydrogen energy infrastructure, a research and technical development strategy as well as the evaluation of the political and socio-economic problems concerning the establishment of a hydrogen society (Hydrogen Network, 2004).
- HyWays - The European Hydrogen Roadmap (2004-2007): The development of a European hydrogen road map for the time periods 2020, 2030, and 2050. Objectives for project partner areas had been proposed, including greenhouse gas emissions as well as favoured hydrogen production and infrastructure technologies. These were coordinated into the proposed road map for the construction of supply infrastructure and end-use technologies. HyWays is the successor of HyNet (HyWays, 2006).
- HyApproval (2005-2007): The goal of this project was to develop a handbook for approval of hydrogen refuelling stations that can be used to certify public hydrogen filling stations in Europe (HyApproval, n.d.).

- HyLights (2006-2008): The task was a coordination action to quicken the commercialization of hydrogen and energy components in the field of transport in Europe. HyLights helped all stakeholders in the preparation of the following critical stage for the move to hydrogen as a fuel and energy vector to be delivered in the long term by renewables (HyLights, 2006).

3 Production costs and retail price of (green) hydrogen

The determination of the current price of hydrogen is a very difficult task, as it varies significantly between each method. Both the production method as well as the way the energy is generated plays an essential role. Table 1 illustrates the various production cost for hydrogen as well as the highest cost driver for each method. However, the production costs represent only a momentary average. For example, inexpensive hydrogen is produced by steam reforming of natural gas and the most expensive hydrogen is generated with the help of solar power from photovoltaic systems.

Method / Process	**H_2-production costs (€/Nm³ H_2)**	**Highest cost drivers**
Natural gas steam reforming:		Cost of fuel (natural gas):
Large plants	0.07 -0.08	50 – 68 %
Small plants	0.17– 0.24	28 – 40 %
Alkaline electrolysis (wind energy)	0.44	Electricity costs: 75 – 85 %
Biomass reforming	0.14 – 0.17	Cost of fuel (biomass): 40 %
Photo-biological production of H_2	0.05 – 11.68 (average 0.54)	Investment costs: Up to 92 %

Table 1: Hydrogen production costs and its highest cost drivers
(Source: Author's illustration, based on (Ministerium für Wirtschaft, Mittelstand und Energie des Landes Nordrhein-Westfalen, 2009)**)**

In order to assess the hydrogen production better, the so called oil equivalent is used as a comparison. For the conversion the given energy amount of hydrogen is equated with the same amount of energy from petrol. Consequently, the result shows that the energy content of 1 Nm³ (≈0.084 kg) hydrogen equals 0.34 l petrol (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie GmbH, n.d., p. 3). In

2013, the global average production of crude oil was estimated to be 86.808 thousand barrels daily (British Petroleum, 2014). In the same year its average retail price was about $91.54 (≈ 68€) per barrel (McMahon, 2014). This means that one litre of petrol equals approximately 0.65 Euro Cent (without taxation) (Aral AG, 2014). Those numbers seem to be far ahead of the current hydrogen production capacity (section 2.2). Nevertheless, as table 1 illustrates, the retail price of green hydrogen strongly depends on the way of its production. The retail price of green hydrogen is about 9.50 €/Kg (Büttner & Stockburger, 2012) whereas the retail price of brown hydrogen is about 7 – 8 €/kg (cleanenergypartnership, n.d.).

4 Hydrogen transportation and distribution

Essential prerequisites for the comprehensive application of hydrogen, is the preparation of a technology which is suitable for daily use at competitive costs as well as the development of a corresponding infrastructure. An adequately dense network of hydrogen refuelling stations paves the breakthrough for a H_2-powered transportation in the long term. For the establishment of a comprehensive hydrogen supply, existing roads, electricity networks, renewables (e.g. wind or solar power plants) as well as (natural gas) pipelines can be used to ensure a on the spot production of green hydrogen. (The Linde Group, n.d.). For this purpose, there are basically four ways to distribute hydrogen. The preference for long distance transportation of hydrogen is LH_2. For the regional supply (< 200 km) hydrogen is usually transported as CGH_2 (Universität Köln, n.d.).

4.1 Pipelines

The hydrogen transport through pipelines is similar to the transport of natural gas. Until 1980, the gas network was used to distribute synthesis gas (town gas), which consisted of 51% hydrogen (Winter, 1993). Although the use of town gas has come to an end, transportation of gas mixtures with up to 25% of hydrogen via the existing natural gas network is achievable (varies from nation to nation; e.g. in the UK it is about 1-5% of hydrogen. However, the main problem is the compatibility of the pipeline material and its components with hydrogen as it may causes embrittlement in steel pipelines as well as permeability in polymeric pipelines (Barbier, 2010, p. 129). In contrast to natural gas pipelines, the transportation of pure hydrogen through pipelines requires a higher compression effort. Current hydrogen pipelines are mainly located where numerous quantities of hydrogen are consumed (e.g. refining and chemical sectors). The European hydrogen network is estimated at around 1600 km (Barbier, 2010, p. 123). The advantages of pipelines are: relatively low maintenance cost and security of supply. The disadvantages, however, are high investment costs (about 10% higher than natural gas pipelines) and the relatively rapid wear of pipelines (if existing natural gas pipelines are used) (Barbier, 2010, p. 129).

4.2 Hydrogen transport by road

Compressed gaseous hydrogen is mainly transported by trucks (short distances up to 300km). In this case, smaller quantities can be transported in single cylinder bottles and larger quantities by long cylindrical tubes or multi-cylinder bundles on trailers. Long cylindrical tube trailers can carry 2000-3000 Nm^3 hydrogen (depending on the number of tubes) whereas the multi-cylinder bundles trailer can transport up to 6500 Nm^3 or 540 kg of hydrogen (depending on the number of cylinders bundles). The major cost drivers of these transport methods are investment, operation and maintenance costs (Barbier, 2010, p. 129). Another way to transport hydrogen by road is the use of cryogenic liquid trucks. Therefore the hydrogen is transported in liquid form (-253°C). In this way up to 10 times more hydrogen compared to CGH2 can be transported (volumetric capacities of 50 000 – 60 000 l). This distribution model is mainly used for the transportation of medium-large amounts of hydrogen and long distances (Barbier, 2010, p. 131).

4.3 Maritime and rail transport of hydrogen

The transportation of hydrogen by sea or inland waterways takes place using so-called LH_2-ships. In this case the hydrogen is transported (just as natural gas) in liquid form. Due to the liquefaction of hydrogen, higher amounts can be transported (compared to gaseous transport). However, in order to keep the evaporation loss as small as possible higher insulation effort is needed. Additionally, to ensure a smooth clearance storage methods and terminals must be developed and established. This causes high costs in turn (Barbier, 2010, p. 133). The transport of hydrogen by train is similar to cryogenic liquid trucks. Nevertheless, hydrogen transportation by rail is hardly ever used. Reasons are lack of bulk purchasers as well as the infrastructural problems mentioned above.

4.4 Refuelling stations

If the hydrogen is used for transportation, a corresponding network of refuelling stations is needed. To distribute hydrogen through a corresponding network of refuelling stations, there are basically two options: the decentralized production of hydrogen directly at the fuel station or the central production in large production plants with subsequent transport to the fuel stations. In 2013, only eleven new hydrogen refuelling stations opened worldwide. In this way a total of 186 refuelling stations are in operation worldwide (March 2014) (TÜV SÜD Industrie Service GmbH, 2014). Current hydrogen refuelling stations mainly deliver CGH2 at 350 or 700 bar to refill the hydrogen tank time efficiently (Barbier, 2010, p. 142). Therefore, the refuelling process itself takes about three minutes. The cost of a standard Linde hydrogen refuelling station is about one million Euros. This technique fits into a 14-feet container (e.g. Green Network's HyTrEc-funded demonstration of such a containerised HRS) and can be carried easily and integrate into existing fuel stations thereby (Dollinger, 2014).

Figure 5: Green Network's HyTrEc-funded demonstration of containerised HRS (Source: HyTrEc-Partnership)

5 Demand of green hydrogen

In future, the need for green hydrogen will mainly be in the transport sector, in special markets and stationary applications. The following illustrates the respective possibilities of the different application areas of green hydrogen. Thus, the increase of these areas could lead to an increase of the sustainable and economical use of green hydrogen.

5.1 Transport sector

Every year, the emissions of fossil fuel based cars count up to several million tons of CO_2. This should be reduced in the future through the use of fuel cells and hydrogen to a minimum. Ideally, no more greenhouse gases are released by cars. In order to achieve this, technical requirements as well as the customers' needs have to be taken into account. Basically, it is conceivable that the mobility behaviour of citizens will change in the future. Nevertheless a system in the long term will not be able to prevail if the restrictions are too severe. Thus, car manufacturers should strive to make fuel cell powered cars comparable to conventional vehicles. This includes, for example, the cruising radius, time of refuelling, dynamics, cold-start capability and the investment cost (Krieg, et al., 2012, p. 105).

The car manufacturers Daimler, Honda, Hyundai, GM, Toyota, as well as other are developing fuel cell vehicles. Different studies show that the hydrogen vehicles have largely reached the level of conventional vehicles in terms of their technical condition. Improvements can still be made concerning investment cost and life expectancy. It is expected that the costs of the fuel cell system can face reductions of about 36 € / kW to around 22 € / kW (Papageorgopoulos, 2014, p. 4). In this case, fuel cell drive technology would be comparable to the cost of today's fossil powered cars. Additionally, the operational life span life of current fuel cells should be increased from 2500h to 5000h. This would correspond to a mileage of approximately 200,000 to 250,000 km (Papageorgopoulos, 2014, p. 4). The market introduction of serial produced fuel cell cars is planned in December 2014 by Toyota. It is estimated that the cars cruising radius is approximately 700 km and its acquisition costs around 50,000 Euros (Preiss, 2014). The market introduction of such cars relies on the further development of green hydrogen production and distribution places (refuelling stations).

5.2 Stationary applications

The stationary application of hydrogen technology is based on fuel cells which are being used for electricity and heat supply. The energy supply of single and multi-family houses is based on two small plants in the power range of 2 to 10 kW (electric), the electricity and heat supply of industrial plants, hospitals and other large buildings is based on cogeneration plants in the power range of 200 kW to 1 MW (electric). In recent years, several pilot plants of the energy supplier were launched to demonstrate and contribute the suitability of daily use. Due to the technical and economic challenges the broad market launch of stationary fuel cell systems is expected from the middle of the next decade (Brennstoffzellen- und Batterie-Allianz Baden-Württemberg , n.d.).

The decentralized production of electricity and heat through the use of fuel cells to supply the industry achieves an overall efficiency of about 90% and an electrical efficiency of over 50%. The generated power can be consumed directly or fed into the grid. The high electrical efficiency of fuel cells reduces resource consumption and CO_2 emissions, especially in combination with green hydrogen. Hence stationary applications of hydrogen are more efficient than conventional combined heat and power (CHP) (by up to 20%) or the conventional production mix of electricity and heat (by up to 30-40%) (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie GmbH, 2011, p. 29). Regarding the industry, stationary fuel cell technology could become a medium-term competitive base-load renewable energy technology.

5.3 Special markets

Special markets are often known as early markets, and thus they usually act as a door opener for the entire technology. Nevertheless, special markets also create applications in the long term, in particular in the field of power supply, business / leisure, light and special vehicles (Garche, 2014, p. 3). The competitor of hydrogen technology is the battery. Although the battery technology is cheaper, its operating periods are lower. The main scope of special markets, in terms of hydrogen, is the off grid application. This, for example, is used where small performance in combination with high operation time is needed (e.g. forklifts, aerospace and boats) (Garche, 2014, p. 31). The support of hydrogen application in special markets may result in a competitive advantage and in new production sites for green hydrogen and fuel cell components. Therefore, special markets offer good condition to demonstrate significant success in the market preparation. Furthermore, it enables fuel cell technology access to a wide range of users and also gains public interest.

6 Stakeholders

Today, more than 50% of the global H_2 production is attributed to the production of ammonia (Figure 1), followed by the use in the petroleum industry for the production and refining of fuels. Smaller amounts are required in the semiconductor industry, metallurgy, the fat hardening, the direct reduction of iron ore and the pharmaceutical art. Furthermore, hydrogen is used in the jewellery industry, in welding, in power plants, in laboratories as well as in the transport sector.

With approximately 90% of the H_2 production the majority of it is processed locally as own use in refineries, without being directly traded. So far, this hydrogen demand could be met by-products internally (IHS Chemical, 2013). The remaining 10% of the annual production is sold by retailing. Hereby the hydrogen is either locally produced (on site) or transported under pressure through pipelines, in gas cylinders as well as in liquid form via fuel tanks. In recent years the hydrogen supply for end users has been increasingly outsourced to gas suppliers (IHS Chemical, 2013). The world's major gas suppliers are Linde - as the largest global producer of gas followed by Air Liquide, Air Products and Praxair. The retailing hydrogen is mainly used by industrial end-users with lower H_2 demand like the electronics, glass, jewellery industry and special user (e.g. LH_2 as rocket fuel).

Nevertheless, the development of the production and distribution of green hydrogen is highly dependent on the shape of its stakeholder. Hence, a strong and diversified stakeholder group is needed. This group needs to come together to examine as well as assess the current position of this emerging industry, exchange ideas on next steps and make contacts to develop a platform for a sustainable and economical hydrogen society. In the next years more and more focus will be put on the usage of renewables in combination with water electrolysis as well as the development and usage of fuel cell technology. Therefore, the following listing shows the stakeholders which are expected to participate in the sustainable and economical hydrogen society:

- Automobile industry
- Institutional investors
- Hydrogen fuel cell developers and operators
- Hydrogen generation equipment manufacturers and suppliers
- Merchant hydrogen producers
- Methanol producers
- National governments
- Refinery operators
- Renewable energy operators and manufacturers
- Research institutions and organizations
- Special markets

7 Action plan

The characteristics of hydrogen provide more benefits than the replacement of the oil economy. Especially the use of green hydrogen offers unprecedented advantages to the quality of life of any being. The benefits of hydrogen are well known. First, hydrogen is not allocated to a few regions, but rather as good as anywhere located (in water, natural gas, etc.) and not limited. As a result, there would be significantly less geopolitical tensions. Additionally, the use of green hydrogen does not cause global warming and can be converted into electricity without any pollution to the environment (Magnusson & Bengtsson, 2008, p. 54). Therefore it is expected that the demand for hydrogen will increase steadily (Chapter 2.2). It is assumed that the demand increases up to 868 billion Nm^3 in 2018 (IHS Chemical, 2013). Reasons for this are:

- A higher national independence from energy imports such as oil or gas,
- the increasing application of hydrogen in the transport sector,
- the increasing demand for refinery products and thus of hydrogen as a reactant,
- the increasing use of hydrogen as a storage medium for the surplus electricity production from renewables,
- tighter environmental regulations and thus a higher demand for hydrogen, for example, the desulphurisation of diesel and gasoline,
- recent increase in the heavy crude oil and thus decreasing H2 quota in the fraction,
- increased activities in the oil sand processing, gas-to-liquids and coal gasification which consume large amounts of hydrogen. (Smolinka, et al., 2011)

7.1 Policy cycle

The policy cycle is a model to divide the policy process, in six or seven steps in most cases. It originates from the U.S. political science and was first formulated in 1956 by Harold Dwight Lasswell (Jann & Wegrich, 2003). Firstly, the policy cycle provides information about how to usefully shape political processes. Secondly the phase model (Figure 5) is a heuristic aid and shows the process and the dynamics of a political process. In mathematics, heuristics are used to achieve a solution as quickly as possible with little computational effort. It is permissible to use estimated values, rules of thumb or other tools, so that although the result is not optimal, but represents a helpful solution for treated problems. The situation is similar with the phase model of the policy setting: Heuristics offers the opportunity to gain targeted insights into political processes. At the same time, only by using heuristic each of the individual phases can be clearly identifiable (Jann & Wegrich, 2003). Thus, the policy cycle seems to be one way to assist the implementation of a sustainable and economical production and distribution.

At the beginning of the policy cycle it is common to have a specific (socio-) political problem or deficit (e.g. CO_2 emissions through fossil fuels). Political, economic or social stakeholders seek, according to their respective interests, to address the problem and to anchor it on the recent political agenda (sustainable and economical production and distribution of green hydrogen). Therefore, to solve the problem policies need to be developed. This step is mostly dependent on the phases of policy making and the implementation of policy and administration. Finally, it should come to the evaluation of the preferred policies and then either concerning the reformulation or to terminate the implementation process of the policy (green hydrogen production and distribution). The following diagram shows the ideal-typical circular arrangement of these individual phases.

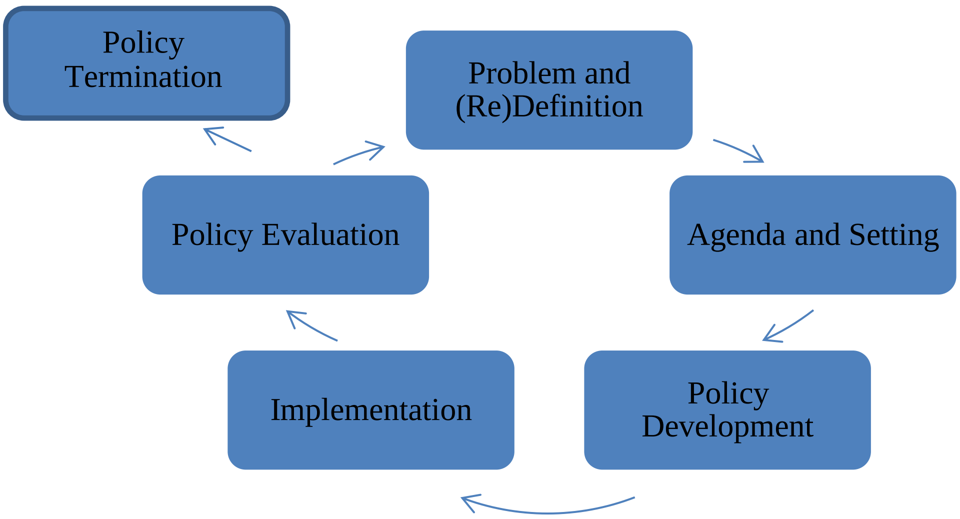

Figure 6: Policy cycle
(Source: Author's illustration, based on (Jann & Wegrich, 2003)**)**

7.1.1 Policy Development

The implementation of green hydrogen technology needs time. However, the demand needs to grow sufficiently fast to compensate costs of infrastructure build up. Meanwhile other options may be needed temporarily. Preferentially, these options should open up the way for green hydrogen rather than create lock out effects. The previous chapters have already contributed significantly to the first and second step of the policy cycle. Thus the following action plan starts with the development of a policy to increase sustainable and economical use of green hydrogen production and distribution.

Although on the long term the introduction of hydrogen into the energy system shows clear benefits to the economy, environment and security of supply, thus significant barriers have to be hurdled to reach the stage where green hydrogen technology reaches cost effectiveness. Therefore, a support of the policy framework is needed to deploy hydrogen financially (e.g. subsidies, tax reduction), regulatory (e.g. quota, standards) and others (e.g. education). To create a policy framework it has to be ensured that its objective is defined. In case of green hydrogen: the general support of sustainability versus the specific support of hydrogen technologies.

7.1.1.1 General support of sustainability

The fundamental idea of the general support of sustainability is to meet (short to medium term) emission reduction targets at minimum costs (HyWays, 2007, p. 30). For this reason hydrogen is generally not part of any short and medium term emission reduction portfolios and therefore contributes insignificantly to reach the Kyoto protocol targets. In addition the contribution of hydrogen to CO_2 emission reduction target for 2020 is scant and its investment costs will be quite high as the technology is not cost-effective, yet (HyWays, 2007, p. 32). Although the impact on the sustainability needs to be visible on the macro level, even small penetration of H_2 vehicles can already contribute to reduce problems and create ecological (e.g. reduction of pollutants and noise in city centres) as well as economic opportunities (e.g. jobs). Nevertheless general support gives both hydrogen as well as competing technologies an advantage over the conventional technology, especially in terms of CO_2 taxation and emission trading (CO_2 certificates).

7.1.1.2 Specific support of hydrogen technologies

In most cases, hydrogen has to compete with both conventional technologies as well as to other innovations (e.g. biofuels). Hence, to strengthen hydrogen production, distribution and end-user application, it needs a specific support scheme. One approach could be to have two linked policy schemes, for instance, a specific support covering the infrastructure (e.g. network charge and incentive regulation) and production (e.g. feed-in systems and capped apportionment) of hydrogen as a fuel as well as the deployment of specific taxation or subsidies for hydrogen cars and fuel cell technologies in general (Roads2HyCom, 2009, pp. 105-106). However, it could also be similar to existing funding mechanism for renewables like it is been done in Germany (e.g. EEG).

7.2 Development of hydrogen infrastructure

Once policies for the production and distribution of green hydrogen have been developed its implementation takes place. The development of hydrogen infrastructure depends on its utilization and demand. If the average utilization is high enough, its cost can be minimalized, thus it becomes attractive for its investors. However, to ensure an increasing use of green hydrogen the expansion of a corresponding infrastructure is necessary. Only through a comprehensive supply of green hydrogen future demands can be met. The following will illustrate which steps have to be taken to fulfil this demand.

7.2.1 Production

Due to high specific investment costs for electrolysers, each unit should be designed as small as possible to achieve cost damping through its high utilization. Further the power input of the electrolysis must be large enough in order to capture a significant degree of the excess electricity production of the installed capacity (e.g. wind turbines). Hydrogen filling stations and wind-hydrogen systems require larger hydrogen production units than available today. Electrolysers with a power input of 1 to 100 MW are required to service future needs. Especially the PEM electrolysis offers a technology which could manage this step technically with a reasonable effort (Smolinka, et al., 2011, p. 36). Alkaline electrolysers still needs optimization in terms of its current density, dynamics of the overall system, load range and compressive strength. A reduction in specific investment cost is expected mainly through economies of scale, less by substitution of materials (Smolinka, et al., 2011, p. 36).

Due to the expected expansion of renewables, additional control energy systems are required. These systems must be installed at critical locations, close to the electricity grid and need to have a wide control range. Compact and highly efficient multi-MW hydrogen production systems can both, provide the control energy that is required, as well as provide decentralized production of hydrogen. In addition the development of large-scale storage methods for hydrogen especially caverns and metal hydrides could help to compensate fluctuations in the electricity grid (Smolinka, et al., 2011, p. 4).

7.2.2 Distribution

Today, the distribution of hydrogen usually takes place directly from its production to its end-user (production site of hydrogen is usually located close to the chemical and petrochemical industries). This, however, will change due to the raising application of hydrogen in the transport sector and decentralized production (Leschus & Vöpel , 2008). As a result, the distribution of hydrogen separates into two parts. One part would be the transmission from the production site to the (inter-) storage (e.g. refuelling stations or caverns). The second part would be from its storage to the end-user. Therefore a corresponding network of road, rail and sea transportation as well as pipelines is needed.

The use of hydrogen in mobility requires the development of an efficient hydrogen infrastructure. The current inventory of hydrogen filling stations is still far away from a comprehensive supply. A significant market penetration of hydrogen in the transport sector is expected by 2025 (Fraunhofer Institut für Solare Energiesysteme, 2013). Hence a powerful network of filling stations must be available up to this time. Standardization simplifies the establishment of hydrogen refuelling infrastructure. Due to the demonstration character of the existing refuelling stations their layout can be diverse. Therefore scale and learning effects are appreciable only in a very limited extent.

Preliminary findings of different hydrogen demonstration projects identified various obstacles which need to be eliminated. Additionally, activities of the stakeholder are necessary to achieve a sufficient infrastructure. A continued close cooperation between the existing and future stakeholders who wish to participate in this new market could eliminate various technological, organizational and market-related obstacles. Therefore a standardization of the service stations promises significant improvements in the area of costs, authorization process, maintenance, reliability, etc., thus, it is the most important technical recommendation for action. 2014, the company Linde, announced the first in series production of a hydrogen refuelling station. Therefore the first step of a standardised hydrogen refuelling station is made.

8 Conclusion and recommendations

This thesis has shown that even though many initiatives and projects concerning green hydrogen had been developed, the implementation of a green hydrogen society is still far away. Several production pathways are available that can produce hydrogen within a limited price range. The analysis of the production methods has shown that due to the high flexibility of PEM electrolysis (to handle electricity from fluctuating renewables) shows the best prospects for a sustainable and economical production of green hydrogen. Although to show market competition its cost efficiency needs to be improved. Nevertheless, alkaline electrolysis should be considered too. The high availability of hydrogen, its production and retail price is likely to be stable and less vulnerable for external effects.

Despite these promising prospects, hydrogen does not enter the energy system by itself, since significant initial barriers have to be overcome. The HyTrEc partnership has identified these barriers throughout the North Sea Region. Further, the partnership developed a paper which co-ordinates the actions identified to address these in the form of a strategy. Especially cost reductions of electrolysis (especially PEM electrolysis), the build-up of the hydrogen infrastructure and other barriers such as regulations, codes and standards. The analysis of the policy framework for the production of green hydrogen has shown that there are no international standards for this case and have not been developed yet. The development of the TÜV SÜD Standard CMS 70 was a first step to such a standardisation. Although this standard is currently only recognised in Germany, it seems to be internationally applicable (e.g. the UK developed a green hydrogen standard based on the TÜV SÜD Standard CMS 70; see 2.4.2).

Based on the presentation of selected initiatives and policy papers of green hydrogen promotion it shows that green hydrogen is recognised as an energy vector with the potential to replace fossil fuels in the transport sector. Thus public funding policy that covers research, development and dissemination on a large scale needs to be developed. Further the list of policies and initiatives shows that large scale demonstration projects are needed to convince the policy makers to implement development programmes for hydrogen. A public private partnership, such as the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) or the Hydrogen and Fuel Cell Technology Platform (HFP), can play a key role in this crucial phase.

By comparing the production cost and the retail price of various hydrogen production methods with petrol it becomes clear that not only the conventional production of hydrogen is profitable but also electrolysis and other production methods have the potential to produce hydrogen economically. In addition, it is shown that the retail price of green hydrogen can already be competitive to conventional produced hydrogen. The glimpse of the hydrogen infrastructure has highlighted that certain pipelines and other infrastructures exist. Nevertheless, due to the raising demand of green hydrogen in the transport sector additional investments is expected. Especially the refuelling stations and pipeline network need to see further development. The contribution of hydrogen in stationary end-use applications seems to be limited to special markets. Therefore stationary applications can contribute its part to security of supply, especially in regard to single and multi-family houses. Penetration rates for stationary applications are low compared to hydrogen in transport.

Hydrogen needs to enter the energy system at the right pace. Not too slow (underutilisation of infrastructure), not too fast (learning effects need time to be incorporated). Hence the action plan illustrates that a targeted approach for the policy development is needed. Through this it becomes clear that green hydrogen needs a specific policy support scheme to make it compatible with alternatives. This could ensure cost effectiveness (minimise the total cumulative cost to reach to the break-even point as quick as possible) and to cover barriers in infrastructure build up as well as end-use applications. Through this the right balance between deployment and technological development can be ensured.

Additionally it is shown that tax and other economic incentives give the producers of and investors in infrastructure the confidence to invest in reliable and sustainable technologies. In addition flexible, dynamic and innovative financing instruments, including directed promotion of industrial growth is needed. Further, once hydrogen reaches increasing competitiveness, the hydrogen support scheme could be replaced by general support schemes (promotion of sustainability). This deployment scheme could facilitate its growth towards mass market. All in all, the answer to the outgoing research question is to be answered with yes. Although the present model does not present concrete actions, yet it serves as a guide for policy makers and thus can contribute to increase the sustainable and economical production of green hydrogen production and distribution. Therefore, the HyTrEc-Partnership supports various activities in developing other more detailed models and strategies for NSR and other regions (e.g. HyTrEc Excel tool– Hydrogen infrastructure and demand model).

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