Mikael Mäkelä

Development of Green Hydrogen Economy and its Feasibility in Electricity Generation in Europe

School of Technology and Innovations
Master's thesis in Science
Energy Technology

Vaasa 2021

FOREWORD

This master's thesis is written in the Faculty of Technology and Innovation at the University of Vaasa and part of the master's degree in Energy Technology. The thesis has been carried out as an assignment for the Growth and Development department of Wärtsilä.

I want to thank my Supervisor, Emma Söderäng, and Evaluator Professor Seppo Niemi for excellent guidance on Vaasa University's behalf. They were always ready to provide valuable support and their expertise for this thesis project. Thank you for the professional views as well as the inspection of the thesis.

A great appreciation and thank you to my instructors Anette Danielsson and Ville Rimali from Wärtsilä, for offering a fascinating research topic and giving continuous assistance during the process. The hydrogen economy-related data provided by Wärtsilä and your personal investment in this project contributed to the progress of the thesis. Thank you also for the exciting discussions about the entire energy transition, which also helped me understand my research's significance.

Finally, I want to thank you, my girlfriend, for continuous support during my master thesis and university studies.

Vaasa,

Mikael Mäkelä

UNIVERSITY OF VAASA	
School of Technology and Innovations	
Author:	Mikael Mäkelä
Title of the Thesis:	Green Hydrogen Economy and its Feasibility in Electricity Generation in Europe
Degree:	Master of Science
Programme:	Energy Technology
Supervisor:	M.Sc. Emma Söderäng
Instructor:	M.Sc Ville Rimali & M.SSc Anette Danielsson
Evaluator:	Professor Seppo Niemi
Year:	2021 **Pages:** 92

ABSTRACT:

One prospective solution to manage the instability of renewable energy sources and reduce emissions in the energy sector is to produce and utilise clean and low-carbon hydrogen. The European Union has announced its target to make hydrogen a main decarbonisation option. This study examines the utilisation of green hydrogen in electricity generation, identifies its challenges and significant benefits. The aim was to provide comprehensive information and estimate the green hydrogen economy and future developments.

This thesis was executed as an assignment for Wärtsilä's Growth & Development department. The exponentially increased objectives in the green hydrogen economy have raised the concern of whether each sector has a sufficient capacity to utilise hydrogen and what happens if green hydrogen cannot be produced as affordable as aimed. These questions point out the need for research about the potential of green hydrogen in electricity generation.

The thesis focused on reviewing and analysing the European hydrogen economy presented in the literature and commercial sources. The aim was to discover a common line between the various perspectives and assess the direction where the European hydrogen economy is most preferably heading in the long term. In this thesis, the different scenarios for using green hydrogen in electricity generation were implemented, based on which each variable's impact was assessed. Also, the competitiveness of green hydrogen under different circumstances was evaluated.

The results showed that green hydrogen has a great potential to become significant long-term energy storage and fuel for electricity generation. Still, it will require development in line with ambitious targets. The use of hydrogen in electricity generation is limited by technical and economic challenges. At current production prices, green hydrogen is not an attractive option to the electricity generation needs. The trend is that sectors such as industry, which currently has the highest hydrogen consumption, also will be the most significant users of green hydrogen, at least in the initial phase.

KEYWORDS: European Union, hydrogen economy, green hydrogen, scenario analysis

VAASAN YLIOPISTO
Tekniikan ja innovaatiojohtamisen yksikkö
Tekijä: Mikael Mäkelä
Tutkielman nimi: Uusiutuvan vedyn markkinoiden ja soveltuvuuden kehitys Euroopassa sähköntuotannon näkökulmasta
Tutkinto: Diplomi-insinöörin tutkinto
Oppiaine: Energiatekniikka
Valvoja: DI Emma Söderäng
Ohjaaja: DI Ville Rimali & VTM Anette Danielsson
Tarkastaja: Professori Seppo Niemi
Vuosi: 2021 **Sivumäärä:** 92

TIIVISTELMÄ :

Yhtenä vaihtoehtona uusiutuvan energian vaihtelevan tuotannon tasapainottamiseksi ja energiasektorin päästöjen vähentämiseksi on tuottaa ja hyödyntää puhdasta, vähäpäästöistä vetyä energiasektorilla. Euroopan Unioni on julkaissut tavoitteensa kyseisten vetyvaihtoehtojen laajasta hyödyntämisestä tulevaisuudessa. Tässä tutkimuksessa tarkasteltiin vedyn hyödyntämistä sähköntuotannossa, sen haasteita ja merkittävimpiä etuja. Työn tavoite oli tarjota tietoa ja arvioita uusiutuvan vedyn markkinoista ja tulevaisuuden kehityksestä Euroopassa.

Työ toteutettiin Wärtsilän energialiiketoiminnan Euroopan Growth & Development osastolle. Vetytalouden kunnianhimoinen kasvutavoite synnyttää huolen, onko vedyn menestymiselle edellytykset sähköntuotannossa. Millaisia vaikutuksia havaitaan, jos vetyä ei pystytä tuottamaan yhtä edullisesti kuin on tavoiteltu? Tällaiset kysymykset osoittivat tarpeen tutkia, millaiset hyödyntämismahdollisuudet uusiutuvalla vedyllä on sähköntuotannossa.

Työssä keskityttiin kirjallisuudessa sekä kaupallisissa lähteissä esitettyjen tulosten ja arvioiden tarkasteluun ja analysointiin. Tarkoituksena oli analysoida, mihin suuntaan Euroopan vetymarkkinat ovat kehittymässä tulevaisuudessa. Tässä työssä rakennettiin myös skenaariotutkimus, jonka perusteella analysoitiin eri muuttujien kehityksen vaikutusta vedyn kustannuksiin ja sitä kautta sen kilpailukykyyn.

Tulokset osoittivat, että vihreällä vedyllä on suuri potentiaali tulla osaksi sähköntuotantoa tulevina vuosikymmeninä, mutta se vaatii kunnianhimoisten tavoitteiden mukaista kehitystä. Vedyn hyödyntämistä sähköntuotannossa rajoittavat sekä teknilliset että taloudelliset haasteet. Uusiutuva vety ei ole nykyisillä tuotantohinnoilla houkutteleva vaihtoehto sähköntuotannon tarpeisiin. On nähtävissä trendi, että sektorit kuten teollisuus, jossa tällä hetkellä vedyn kulutus on suurinta, tulevat olemaan merkittävimpiä uusiutuvan vedyn hyödyntäjiä lähivuosina.

AVAINSANAT: Euroopan Unioni, vetytalous, uusiutuva vety, skenaarioanalyysi

Contents

Figures

Tables

Abbreviations

ALK	Alkaline
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CO_2	Carbon dioxide
EEA	European Environment Agency
EHB	European Hydrogen Backbone
EPA	United States Environmental Protection Agency
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FRP	Fibre Reinforced Polymer
H_2	Hydrogen
ICE	Internal Combustion Engine
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOH	Levelized Cost of Hydrogen
LRF	Linear Reduction Factor
LHV	Lower Heating Value
MgH_2	Magnesium hydride
NG	Natural Gas
NIST	The National Institute of Standards and Technology
NO_x	Nitrogen Oxide
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
ROW	Rights of Way
SOFC	Solid Oxide Fuel Cell
SMR	Steam Methane Reforming

1 Introduction

Five years since the signing of the Paris Agreement, global climate change is finally driving the development of the energy sector. The agreement has set the framework for common targets to slow down and finally stop global warming. In addition to these global targets, European Union (EU) has established its objectives to reduce greenhouse gas emissions by at least 55 % by 2030 and make the EU climate-neutral by 2050. During the Coronavirus pandemic in 2020, European Commission released the recovery plan that, alongside other support measures, will also focus on the European Green Deal and allocate the investments in the growth of wind and solar energy sources. The European Commission aims to enable a kick-start for clean, renewable hydrogen as a main decarbonisation option. In this thesis, the term green hydrogen is the most commonly used term for clean hydrogen produced via renewable electricity. The European Commission has published “A hydrogen strategy for a climate-neutral Europe” in July 2020. This strategy was used as the basis for this master's thesis.

For a long time, hydrogen has been produced by using fossil fuels, and it is still the most cost-effective way to produce hydrogen. However, due to the rapid decline in the costs of renewable energy, green hydrogen has become more competitive, and the EU is driving to continue this enhancement. In addition, this development is facilitated by the evolution of electrolysis technology as well as the urgency of decarbonisation. The EU's extremely ambitious goal is to achieve 2X40 GW hydrogen markets in Europe by 2030. Since the hydrogen strategy was published by the European Commission, various analyses have been released in the previous months. Several actors have strived to analyse the consequences of the European Union's strategy and evaluate how likely ambitious targets can be reached. Together with scientific research texts, the thesis examined various commercial analyses written on the basis of the EU's hydrogen strategy.

Ambitious goals are impossible to achieve without the commitment of the EU's member states, and actually, 26 member states have already signed the “Hydrogen Initiative”. In 2020, European Commission and six member states published their hydrogen strategies (Adler 2020). The 2X40 GW green hydrogen initiative means that 40 GW will be produced inside the EU and another 40 GW, mainly in Northern Africa and Ukraine, where conditions are ideal for renewable energy production. (Hydrogen for Climate Action 2020). Currently, the United States has the largest production capacity of low carbon hydrogen and electrolysis production. In addition to the US and the EU, other countries have shown their interest in the hydrogen economy and some have already taken preliminary steps to promote the green option. Some of the reports used in this thesis have been published in the UK or US, and different currencies are used. Currencies were converted into euros with the conversion rates of 1 € = 1.12 $ and 1 € = 0.9 £.

A great amount of discussion and debate has been around green hydrogen recently. The potential of green hydrogen as a remarkable decarbonisation option has begun to be recognized. However, hydrogen is not a new invention in the energy sector, and it has been exploited for decades. Hydrogen has always been associated with challenges in terms of production, emissions, supply, safety, and cost-effectiveness. These challenges have not suddenly disappeared. In particular, the drop in the price of renewable energy and the development of key technologies have made green hydrogen a more attractive investment object.

The benefits of hydrogen as storage and carrier of renewable energy over a long period of time have also been further explored. However, deployment-related concerns of green hydrogen have also emerged. Therefore, this study concentrated on assessing what would be the most likely outcome under unfavourable circumstances, for example, if green hydrogen cannot be produced at an affordable price as planned or technical challenges cannot be solved in a rapid timeframe. The scope of the thesis was limited to approaching the topic mainly from the electricity generation point of view.

The thesis had to clarify the feasibility of green hydrogen in electricity generation and estimate the future development progress. The green hydrogen can be utilised in numerous ways in electricity generation. The aim was to find out the most cost-efficient way to use hydrogen at the moment and what future developments look like in the European market area. The thesis focused on hydrogen transportation by pipeline and storage issues of clean hydrogen from an electricity generation perspective. Transportation methods by trucks, ships, and trains were excluded from this thesis's research area because the pipeline has been found the most feasible option for transporting hydrogen. The objectives set by the European Union for the growth of green hydrogen were in the background throughout the thesis to assess their feasibility.

The first part of the thesis focuses on the European situation and objectives set by the European Commission. This section reviewed the latest released hydrogen plans and evaluated the estimated costs and energy volumes. Identifying the challenges of the European hydrogen strategy that may be faced in the coming years was one of the main items in the first section. At an overall level, the assessment of the hydrogen market situation within the EU was also one of the objectives of the initial phase of the thesis. The first part also analysed the market potential of green hydrogen from a demand perspective in different sectors. The middle part of the thesis focused on studying green hydrogen from the point of view of electricity generation, for instance, by comparing different technologies. This part investigated the research question about how feasible hydrogen, in general, is in electricity generation. Comparison of pipeline transportation methods, their benefits, and challenges was examined. Capacity and main challenges in hydrogen storage were also explored in the middle part of the thesis.

Chapter 5 presented the scenarios' results, which assessed the feasibility of green hydrogen from a practical point of view. The analyses and theory presented in the thesis were used as a basis for the calculations. The impact of each variable on the final price was assessed, and the cost competitiveness of green hydrogen in blends was explored.

After the scenario analysis, the discussion chapter considers the validity of the results and possible market trends of green hydrogen. Further research subjects were also identified around the topic. Figure 1 shows the main hydrogen production methods and a simplified overview of green hydrogen from production to utilisation in electricity generation. The green route in Figure 1 shows the most environmentally friendly but also the most expensive way to hydrogen production and utilisation. However, the costs of technologies for the production and transportation of green hydrogen are decreasing most rapidly.

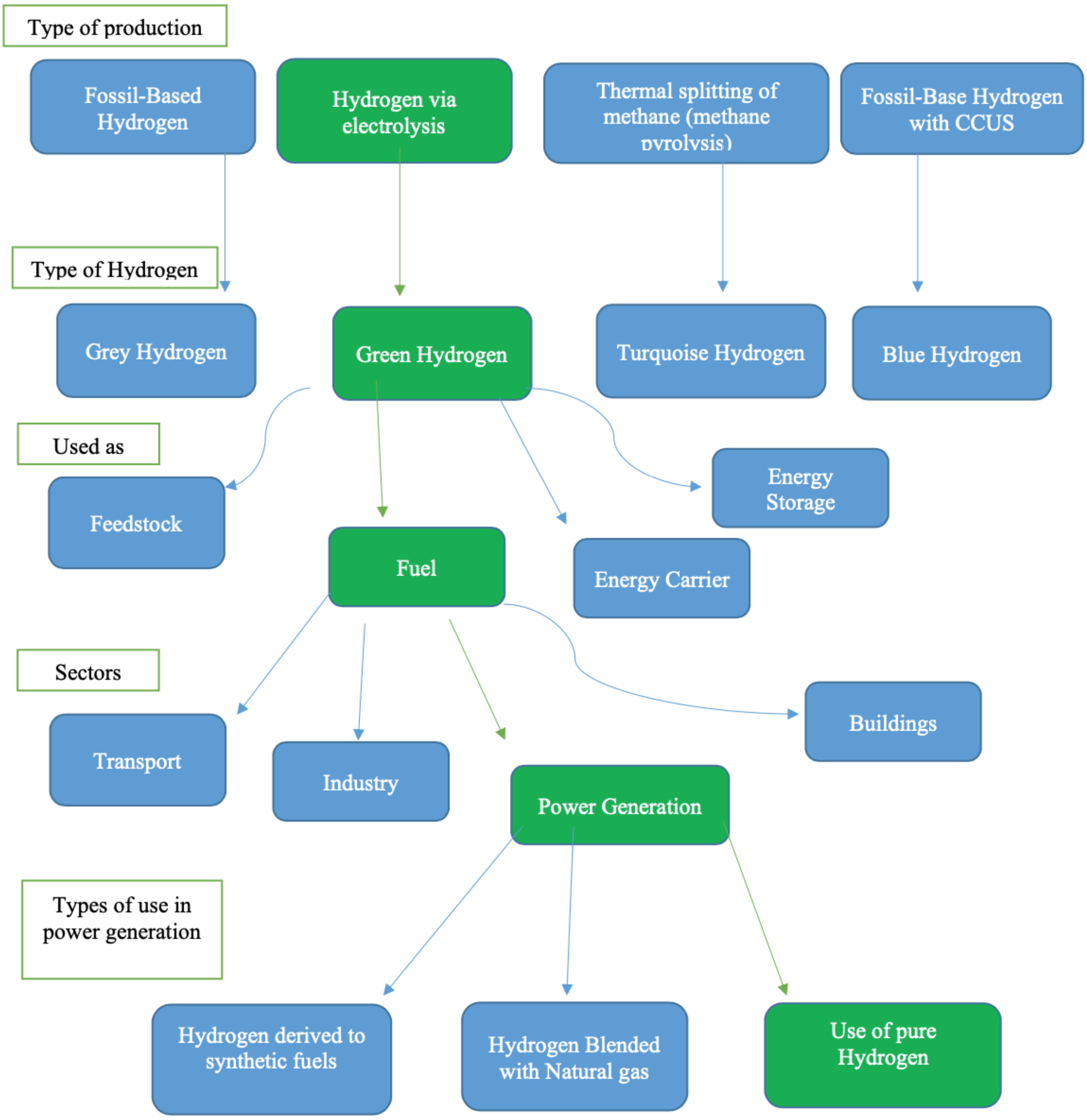


Figure 1. Simplified route from green hydrogen to electricity generation.

2 Hydrogen

Hydrogen is the most common and the lightest element in the universe, consisting of only one proton and one neutron per atom. Hydrogen shows up in multiple compounds, the most common of which is water. Low emissions can be achieved through the use of hydrogen, and it is one of the main advantages of this chemical element. (Gupta 2009). Due to this, hydrogen has tremendous potential to significantly impact the ongoing energy transition and become a notable decarbonisation enabler.

2.1 Hydrogen categories

Hydrogen can be produced in several ways from different energy sources. The use of hydrogen itself does not cause harmful emissions but the method of hydrogen production needs to be taken into account when dividing hydrogen into different categories. Hydrogen can be named green when produced via water electrolysis, and the process is powered by renewable energy. However, currently, the most popular hydrogen production methods are not environmentally friendly as they utilise fossil fuels, producing grey hydrogen. Blue hydrogen represents hydrogen produced in a similar way as grey hydrogen but where carbon is captured and stored. Also, there are also several different ways to produce hydrogen. Colour codes are not the same everywhere and can sometimes vary by country and source. (Dodgshun 2020).

2.1.1 Grey hydrogen

The most common grey hydrogen production process is called steam reforming of natural gas (NG). In the Steam Methane Reforming process (SMR), methane reacts with water and gives carbon dioxide and hydrogen as reaction products. (Federal Ministry for Economic Affairs and Energy 2020: 28). The main disadvantage of grey hydrogen is a fossil fuel as a feedstock of the process and consequent carbon formation during the reforming. The most significant advantage of grey hydrogen is its cost-effectiveness. According to the IEA, the cost of grey hydrogen is approximately 1.5 €/kg. (Willuhn 2020).

2.1.2 Green hydrogen

In the most environmentally friendly option, hydrogen is produced using renewable energy as a source. Electricity is fed to an electrolyser which needs water and electricity to produce hydrogen and oxygen ecologically. The end product is called green hydrogen, which is an object of this study as well. This kind of hydrogen is also called clean hydrogen but can be easily confused with other low-emission hydrogen categories, which are presented in the following chapters. In the deployment of clean hydrogen alternatives, the transparency of energy products is essential. For this, a certification system CertifHy is being developed to guarantee the origin of a product and its environmental attributes. (CertifHY 2019). The main challenge for green hydrogen is its high production costs compared to grey hydrogen.

2.1.3 Blue hydrogen

While grey and green hydrogen are the two best-known categories of hydrogen, some subcategories have been presented to reflect the properties between clean and polluting hydrogen. This category is blue hydrogen which is not as clean as green hydrogen but more environmentally friendly than grey. Production of blue hydrogen mostly corresponds to the process of grey hydrogen. Fossil fuels are usually raw materials, but blue hydrogen production processes use Carbon Capture and Storage (CCS) Technology. It means that carbon emissions released in the process are recovered and not entered into the atmosphere. (Federal Ministry for Economic Affairs and Energy 2020: 28).

It is also possible to use Carbon Capture, Utilisation and Storage (CCUS) technology which will utilise the captured carbon, for example, in the production of synthetic fuels. According to the IEA, the use of CCUS technology will increase costs by 50 – 70 € per captured ton of carbon dioxide. Approximately 9.3 kg of carbon dioxide is produced per 1 kg of hydrogen production in the SMR process (Rapier 2020). If it is assumed that 90 % of produced CO_2 can be captured and the price range is the same as in the IEA report, CCUS technology will add costs 0.42 – 0.59 €/kgH_2. Such a large increase in hydrogen per kilogram price will significantly affect the profitability of hydrogen in electricity generation.

2.1.4 Other hydrogen colours

Turquoise hydrogen is one of the most commercially unknown category of hydrogen production. This type of hydrogen is produced via methane pyrolysis where heating methane produces hydrogen and solid carbon. (Federal Ministry of Economic Affairs and Energy 2020: 28). In this case no CO_2 emissions are generated but due to use of fossil fuel in the process it is not as clean as green hydrogen production.

In addition to the above-mentioned ways to produce hydrogen, other options such as pink hydrogen produced using nuclear energy are also defined in the hydrogen economy. This thesis focuses on green hydrogen, its market, and feasibility in electricity generation. Investing in green hydrogen research makes sense, as several changes, such as hydrogen reports from the EU, several member states and technological progress, which will promote green hydrogen deployment have occurred recently.

2.2 Hydrogen strategy in the EU

The European Union is aiming to implement emission reduction targets and facilitate clean energy transition in Europe. Hydrogen is not the only solution in energy transition, but the European Commission's hydrogen strategy calls for a significant increase in hydrogen use in various sectors. For hydrogen to be useful in energy transition, it needs to be produced using clean energy sources instead of fossil fuels.

The EU is planning for significant emission reduction in hydrogen production in the coming years and even to reach carbon-free production. At present, the EU's hydrogen production releases 70-100 million tons of carbon dioxide into the atmosphere annually. A typical passenger car emits 4.6 tons of CO_2 per year (EPA 2018), so hydrogen production in the EU is equivalent to annual CO_2 emissions of 15-22 million passenger cars. In other words, CO_2 emissions from hydrogen production correspond to almost 10 % of European greenhouse gas emissions from transport, which was equivalent to 1097 million tonnes of CO_2 emissions in 2018 (European Environment Agency 2020).

2.2.1 Ambitious target

Due to the emissions from current hydrogen production, the European Commission recovery plan and hydrogen strategy's main options are green and other low-emissions alternatives such as blue hydrogen. Goals are extremely ambitious, and the years 2030 and 2050 are most commonly used in different scenarios. One of the main targets is to reach an electrolyser capacity of 40 GW in the EU by 2030. At the time of writing in December 2020, the total electrolyser capacity in Europe is only less than 1 GW, so rapid growth of hydrogen production by electrolysers is expected (European Commission 2020b). One gigawatt of capacity corresponds to the amount of 300 operating electrolysers and the production size only four percent of total hydrogen production in the EU. The estimates of the green hydrogen impact for the economy and society vary a lot between different scenarios. For instance, according to the European hydrogen strategy, necessary cumulative investments for scaling up the green hydrogen could range from 180 billion euros up to 470 billion euros. To meet a quarter of global energy needs by hydrogen, the 2020 Gas report states that over 9.3 trillion euros are required by 2050. (Snam, IGU & BloombergNEF 2020).

The green hydrogen target (2X40 GW) is explained more comprehensively in the “Green Hydrogen Investment and Support Report”. The report also divides the 665 TWh of hydrogen production target by 2030 (FCH JU 2019) into more specific sections. The report shows that the target includes only 173 TWh of new green hydrogen production in the EU. The rest of the production consists of imported green hydrogen 118 TWh, current grey hydrogen upgraded to low carbon Hydrogen 324 TWh, and new low-carbon Hydrogen production of 50 TWh (Hydrogen Europe 2020: 4). Therefore, new green hydrogen production is only 26 % of the total green H_2 target. It still requires extensive investments in renewable energy sources.

Table 1 is published by Trinomics (2020) in their hydrogen technologies report. It shows how the economic and social impacts of green hydrogen development are expected to distribute between the 28-EU member states. The data in Table 1 is not straightforward if the values are scaled to each country's size. For instance, when the demand of green hydrogen is related to the population, Finland is the country with the highest demand per citizen (0.91 MW). There are several reasons for that, but the Finnish steel industry, which has a great hydrogen-demand potential, can be considered a significant single factor. With the same comparison technique, the Netherlands is the country with the second-highest demand/citizen (0.69 MW). Overall, the results show that green hydrogen is expected to be an EU-wide solution for the energy sector decarbonisation.

Table 1. Estimated outcomes according to the EU scenarios by countries (Trinomics 2020)

Member State	Hydrogen demand (TWh_{H2}/a)	Electrolysis capacity in GW_{el} (SMR+CCS capacity in GW_{H2})^2	Avoided fossil fuel imports (TWh/a)	Value added (million EUR)	Jobs (FTEs)
Austria	2 - 6	0.6 - 2.0	4 - 11	303 - 980	3324 - 10509
Belgium	1 - 7	0.4 - 2.3	2 - 8	224 - 1140	2525 - 10735
Bulgaria	0.8 - 1.4	0.3 - 0.5	1 - 2	109 - 190	3354 - 6001
Croatia	0.1 - 0.4	0.03 - 0.2	0.1 - 1	13 - 70	177 - 591
Cyprus	0.02 - 0.1	0.01 - 0.1	0.03 - 0.1	5 - 30	97 - 599
Czech	0.4 - 2	0.1 - 0.6	1 - 3	77 - 290	535 - 1330
Denmark	0.4 - 2	0.1 - 0.6	1 - 2	66 - 290	558 - 1442
Estonia	0.01 - 0.1	0.005 - 0.05	0.03 - 0.2	2 - 20	70 - 483
Finland	1 - 5	0.3 - 1.1	3 - 11	273 - 900	2728 - 8854
France	4 - 20	1.2 - 5.3	8 - 27	669 - 2680	10379 - 33648
Germany	9 - 41	3.0 - 13.7 (1.1 - 5.0)	19 - 67	1918 - 7620	23192 - 82799
Greece	1 - 3	0.4 - 1.0	2 - 4	229 - 540	4450 - 10432
Hungary	1 - 2	0.3 - 0.9	1 - 3	134 - 360	721 - 1548
Ireland	0.1 - 1	0.0 - 0.3	0.2 - 1	15 - 130	246 - 1797
Italy	4 - 20	1.3 - 6.7	7 - 26	779 - 3510	11509 - 41760
Latvia	0.05 - 0.2	0.02 - 0.1	0.1 - 0.3	8 - 30	316 - 1222
Lithuania	0.1 - 0.7	0.04 - 0.3	0.1 - 1	18 - 120	569 - 3742
Luxembourg	0.1 - 0.4	0.1 - 0.3	0.2 - 1	44 - 160	420 - 1531
Malta	0.01 - 0.05	0.003 - 0.03	0.01 - 0.04	1 - 10	33 - 224
the Netherlands	3 - 12	0.8 - 3.6 (0.3 - 1.5)	4 - 14	460 - 1930	5112 - 18204
Poland	2 - 6	0.7 - 1.7	3 - 8	343 - 870	3597 - 8608
Portugal	1 - 7	0.3 - 2.7	1 - 8	92 - 740	2500 - 18450
Romania	1 - 2	0.3 - 0.8	2 - 3	156 - 350	1925 - 4440
Slovakia	0.4 - 1.1	0.1 - 0.4	1 - 2	59 - 160	1285 - 3609
Slovenia	0.1 - 0.2	0.02 - 0.1	0.1 - 0.3	12 - 30	270 - 686
Spain	4 - 17	1.0 - 4.1	7 - 20	604 - 2360	10527 - 35827
Sweden	2 - 5	0.4 - 1.2	4 - 11	312 - 880	1106 - 2593
UK	4 - 21	1.1 - 5.6 (0.5 - 2.5)	7 - 27	664 - 2940	12532 - 45975
EU28	**42 - 183**	**13 - 56 (1.9 - 8.9)**	**80 - 259**	**7 590 - 29 330**	**104 060 - 357 630**

Table 1 shows the German leadership in the deployment of a low-carbon hydrogen economy in the coming years. Germany's outcomes are in their own order of magnitude than other EU's member countries. Based on Table 1, it can be interpreted that Germany will gain the strongest hydrogen economy in Europe. Germany will have the most significant demand, electrolysis capacity, added value, jobs created, and the largest amount of fossil fuel use avoided.

One misleading factor is that the place where the required hydrogen will be produced does not appear in the table. For example, Germany's hydrogen strategy states that the domestic generation would not cover all of the hydrogen demand and favourable conditions for renewable energy in other EU countries will be utilised to produce clean hydrogen to Germany. However, the same report also indicates that the Federal Government aims to enhance the production sites in other partner countries. The role and name of these countries are not further explored in the strategy. The actions made by the Federal Government clarify intentions, such as the fact that the German aims to finance green hydrogen projects in Morocco, Tunisia, Brazil, Chile, and South Africa in total with two billion euros. (Gas to Power Journal 2020). This information was published five months after the release of Germany's hydrogen strategy.

2.2.2 Necessary actions

In order to achieve these ambitious goals, extensive actions are needed urgently in the EU. Activities can be roughly divided into political and economic sections, as done in the hydrogen report published by Fuel Cells and Hydrogen Joint Undertaking (FCH JU 2019). Towards 2030, eight billion euros investments to scale-up the hydrogen economy are expected annually to achieve the EU's target to build a 665 TWh size hydrogen economy in Europe. As a comparison, over 20 times more money is invested in the energy and automotive assets in Europe annually, which shows that these goals are feasible if there will be enough ambition.

The EU has great potential to expand its hydrogen markets by taking advantage of its strengths. The EU is a leading player in the hydrogen and fuel cell value chain, and that potential needs to be utilised effectively in the coming years. Besides, robust research competence and a strong commitment to climate targets can be seen as a significant benefit of the EU. Moreover, the EU already has an extremely broad gas network that can be exploited for hydrogen use. Further information about the gas network in the EU and its opportunities and challenges are presented in Chapter 4.

In FCH's hydrogen report, eight individual recommendations on how green hydrogen can be a profitable decarbonisation option are explored. The list below summarizes the recommendations of the report.

1. Industrial actors and regulators are required to set long-term decarbonisation options also taking into account the production and distribution.

2. The industry in Europe need to allocate the assets to the development of hydrogen and fuel cell technologies.

3. Gas companies together with regulators are required to work towards a low-carbon gas network (e.g., feed-in tariffs).

4. Regulators have to facilitate the use of electrolysers. Access to the renewable energy markets is a critical condition for profitability.

5. Investment needs to be allocated to the refuelling stations of hydrogen and give a strong signal to car manufacturers to scale up the fuel-cell vehicle production.

6. Make clean hydrogen production more attractive than grey hydrogen through various regulatory measures.

7. Encouraging low-carbon hydrogen options (Green and Blue). Prove that CCS technology can be used to achieve very low carbon levels in production.

8. Scaling up the existing hydrogen applications and developing and enabling the new applications.

As the recommendations show, the actions are required from numerous actors and in several different sectors. Individual factors are not enough to allow the growth of green hydrogen; instead, all operators need to work together. In addition, all eight recommendations interact with each other, and no single point can be the sole focus. If all of the functions can not be met, it may cause some ultimate challenges to reach the green hydrogen economy objectives as planned.

2.3 Hydrogen as fuel in electricity generation

Hydrogen is a highly light element with an atomic weight of 1.008 u. The energy density per mass of hydrogen is very high, which is why hydrogen has been used, for instance, as a launch fuel for space rockets. However, energy content per volume is extremely low in hydrogen, which causes problems with space and high flow rates. If there is no access to a hydrogen transportation network, large hydrogen tanks are needed, which may cause additional hurdles to end-users with restricted space for storage facilities. However, due to low emissions of hydrogen use, it is considered to be an alternative fuel of the future by replacing some major fuels like natural gas, oil and coal. (Momirlan & Veziroglu 2005).

Several different technologies can be utilised to produce electricity via hydrogen. The following sections discuss the most relevant and advanced electricity generation technologies. Three different technologies, gas turbines, fuel cells, and engines, are most likely to be the leading solutions for hydrogen utilisation in electricity generation in the future. Technologies are practically in the product development and pilot phase. This review does not focus on the availability and transport issues of green hydrogen but only on the properties of the power production technologies: fuel cells, gas turbines and internal combustion engines.

2.3.1 Fuel cell technology

A fuel cell is an equipment that can convert chemical energy like hydrogen to electricity by producing almost no emissions. (Wang & Jiang 2017). Proton exchange membrane (PEM) is a typical application of fuel cell technologies that contains an anode, a cathode and electrolyte (membrane) between them. Oxygen is supplied to one side and pure hydrogen to another side. The membrane passes through the positively charged atoms of hydrogen. In order to equalize the system, negatively charged hydrogen atoms move to another side via different paths, creating an electric current. In turn, the reaction of hydrogen and oxygen produces only pure water as a product.

Fuel cells have been found to be a reliable option to reduce greenhouse gas emissions and one of the best features is their high flexibility in operation. Proton-exchange membrane fuel cell (PEMFC) is one of the most mature fuel cell technologies, especially in-car use. High power density can be achieved with PEMFC technology, and operating temperature is typically between 20 °C to 100 °C. Another option is solid oxide fuel cells (SOFC), which are high-quality devices using ceramic and non-corrosive materials and have an ability to operate at high temperatures up to 1000 °C. Due to high operating temperatures, SOFCs can utilize a wide range of fuels with high efficiency and are therefore considered a suitable option for power supply in the kW to MW-size range. (Wang & Jiang 2017).

Fuel cell technology has the potential to be a green electricity producer, but costs need to be cut. Capital expenditures (Capex) of a fuel-cell technology are too high at the moment. One of the challenges in fuel cell technology is the inefficiency of the process. Figure 2 shows the whole path from renewable energy and electrolysis to electricity production by fuel cell technology. As it is visible, the efficiency of the route is not very high due to several major losses during the path. 1 TWh of renewable energy production has been selected to be an example and only 0.33 TWh of electricity is produced from the fuel cell.

The Hydrogen Roadmap report released by FCH is used to determine the average losses in Figure 2. The estimation of electricity and hydrogen transportation losses is based on Professor Van Wijk's study (2019). Laban's (2020) master thesis on hydrogen storage has been used to estimate losses in storage. Electrolyser efficiency is determined based on the IRENA report (2020), and fuel cell efficiency is used based on the fact sheet released by the U.S. Department of Energy (2015). It is noted that even if a fuel cell seems to be a promising option for energy shifting, cost reduction, and a more efficient process is required. Figure 2 gives an indicative estimation of losses.

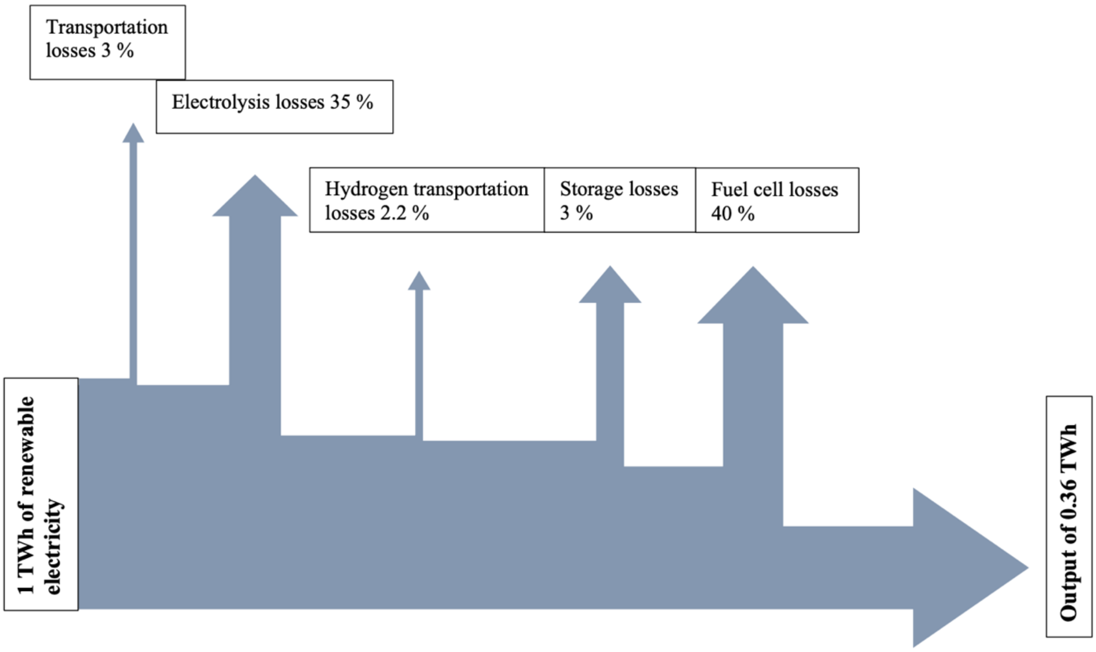


Figure 2. Efficiency of "Power to Gas to Power" shifting process implemented by fuel cell

2.3.2 Gas turbines and internal combustion engines

Hydrogen combustion has been practiced in gas turbine plants for decades. In most cases, a mixture of hydrogen and natural gas has been the fuel, but 100 % pure hydrogen has also been tested. The results have indicated that turbines are valid challengers for fuel cells, especially in terms of reliability and costs. One of the targets in gas turbine development is to operate 100 % hydrogen with low NOx emissions in the coming years. A lot of research about hydrogen turbines has been done to solve how to control NOx emissions, for example, by adjusting the velocity of flame and premixing properties. (Cappelletti & Martelli 2017). Kawasaki Heavy Industries announced in July 2020 that they had developed 100 % hydrogen operating gas turbines with dry low-NOx technology in cooperation with Obayashi Corporation and New Energy and Industrial Technology Development Organization (NEDO). (Global.Kawasaki.com 2020).

Another option for hydrogen combustion is to use an internal combustion engine as a power producer. In engines, a wide range of hydrogen flammability provides an opportunity for a broad power output range by variation of the air/fuel mixture ratio. The combustion of pure hydrogen in an internal combustion engine is not yet utilised commercially, but the technologies have been studied occasionally, and the interest has again strongly increased. For instance, smart technology company Wärtsilä has researched hydrogen as a fuel for over 20 years and already used 60 % hydrogen blend with natural gas. In May 2020, Wärtsilä announced that its gas engines would use 100 % pure hydrogen in the future. (Wärtsilä 2020). This development brings a new way to generate electricity via pure hydrogen to the electricity markets. Suppose the future situation is that hydrogen is only used during the consumption peaks instead of baseload. In that case, the hydrogen engine could be a profitable option due to its good adjustability and quick ramp-up time.

The use of hydrogen in gas turbines and internal combustion engines have some common benefits and disadvantages. For instance, the use of blended or pure hydrogen can reduce the CO_2 emissions when compared to the use of natural gas, but NOx emissions could rise due to high combustion temperature when nitrogen of air oxidizes to NOx. (Verhelst & Wallner 2009). As mentioned, using a blend of NG and H_2 does reduce the amount of carbon dioxide released during combustion. Still, the reduction is smaller than the volume-based mixture ratio because hydrogen has less energy per unit of volume than natural gas. That phenomenon was examined in more detail through calculations in Chapter 5.

The use of hydrogen in internal combustion engines has several benefits and challenges, summarized in Table 2 below. The points have been taken based on the Master thesis by Philip Westberg (2020). Based on Table 2, it could be concluded that the divergent properties of hydrogen affect its feasibility in the use of internal combustion engines. It is worth noting that the same feature can have both positive and negative impacts simultaneously. Most of the negative effects are not related to performance but rather to safety issues. Therefore, it is likely that research and development will focus on promoting combustion control technologies such as shut-off systems like valves. The table contains the properties that can be observed in hydrogen use compared to the typical gaseous or liquid fuels.

Table 2. Pros & Cons of hydrogen fuelled ICE (Westberg, Philip 2020).

PROS	Positive effect	CONS	Negative effect
Wide flammability range	Low exhaust temperature and emissions	Low-density	Storage requires a lot of energy More space in combustion chamber Lower power output
Auto-ignition temperature	Ignition without external energy source	Light gas	Penetration into combustion chamber
High compression ratio	Better efficiency	Low quenching distance	High chance of backfire
High flame speed	Close to the ideal engine cycle	High flame speed	Higher flame temperature. Higher NOx emissions
Ability to disperse in air (Diffusivity)	Uniform mixture for Otto-engines	Ability to disperse in air (Diffusivity)	Increased risk of safety hazard In case of leakage (Diesel)
Low minimun ignition energy	Easy to ignite	Low minimum ignition energy	Prone to pre-ignition

3 Feasibility of green hydrogen

This section examines, based on various estimates, which industries will most probably have the greatest demand for green hydrogen and the profitability prospects in different industries. Green hydrogen can be used as such or be converted to other forms.

3.1 Demand

In order for green hydrogen to be successful and achieve a significant position in the energy market, extensive demand in several different industries is required. Hydrogen can be exploited in the numerous sectors of which transport, power generation, building's heating, industry energy, and industrial feedstocks are considered primary consumers. Decarbonisation is exceedingly challenging in specific sectors such as transportation. Green hydrogen could provide a possible solution to this challenge as a clean fuel option. One of the main advantages of hydrogen is its lightness. One kilogram of hydrogen contains approximately 150 times more energy than the equivalent weight of a lithium-ion battery. When a more extended range is desired, electric cars' mass needs to be increased due to larger batteries, while the mass of hydrogen fuel cell cars remains on the same level.

There is a strong focus on minimizing the weight to achieve the best possible fuel consumption and aircraft performance in aviation. Therefore, hydrogen as a fuel is a desirable option from an aviation point of view. (Tsakiris 2019). In addition, hydrogen is also considered to become one of the primary fuels for road traffic. Greenhouse gas emissions in transportation have increased in previous decades while overall emission levels have reduced in the EU. In Fuel Cell Electric Vehicles (FCEV), hydrogen is used to produce electricity to run an electric motor. According to the European Commission's hydrogen strategy, public and commercial options like taxis and local busses can be early adopters of hydrogen use. Based on various analyses, a potential bottleneck in

the transportation sector could be the hydrogen distribution network, complex fuelling stations, pressurized gas tanks, and fuel cell technology inefficiency.
Battery electric vehicles (BEV) have already gained the strongest market in vehicles powered with electric motors. In the use of hydrogen vehicles, building a proper distribution network for hydrogen is slow, expensive and challenging. At the same time, the BEVs owner can charge their battery even at home without a significant investment. Further technological developments will be expected, especially in heavy-duty road vehicles and fuel-cell trains. These parts of transportation are predicted to have the greatest potential for the use of hydrogen. The European Commission announced the Sustainable and Smart Mobility strategy in December 2020, according to which the EU would have about 30 million zero-emission vehicles operating by 2030. (European Commission 2020d). The importance of the development of hydrogen alternatives in the transportation sector is highlighted in the report, but the actual target for the number of hydrogen-powered vehicles is not set in the strategy.

Some hydrogen-based car models are already available in the markets, but as high popularity as in electric vehicles is not yet achieved. Impracticalities such as storing hydrogen in a pressurized tank, transporting and distributing gas networks have restrained the demand. The industry aims to develop new innovative and efficient solutions to the challenges. One of the latest is POWERPASTE, developed by a Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFMAN. The basic idea is to store hydrogen in solid magnesium, whereby a magnesium hydride MgH2 is formed. When the compound reacts with water, it releases hydrogen, which is used as a fuel. Thus, one tank for paste compound and one tank for water is required, but a pressurized gas tank and, therefore expensive infrastructure costs can be avoided. According to a press release published by the institute in February 2021, higher energy storage density than in batteries and pressurized tanks can be achieved. The paste was initially designed for e-scooters, but the pilot plant is planned to produce a paste for other vehicles as well. (IFAM 2021).

The European Commission's ambitious target shows that transportation could gain the largest share of hydrogen consumption by 2050. Various scenarios are presented in Figure 3, published by Fuel Cells and Hydrogen (FCH JU 2019) in cooperation with the EU. Business as usual scenario means that developments in the hydrogen economy remain at current levels, and no major changes are expected. The ambitious scenario, in turn, refers to a situation where various measures are taken to increase the final demand for hydrogen. Clear differences are visible between these two scenarios, especially in 2050.

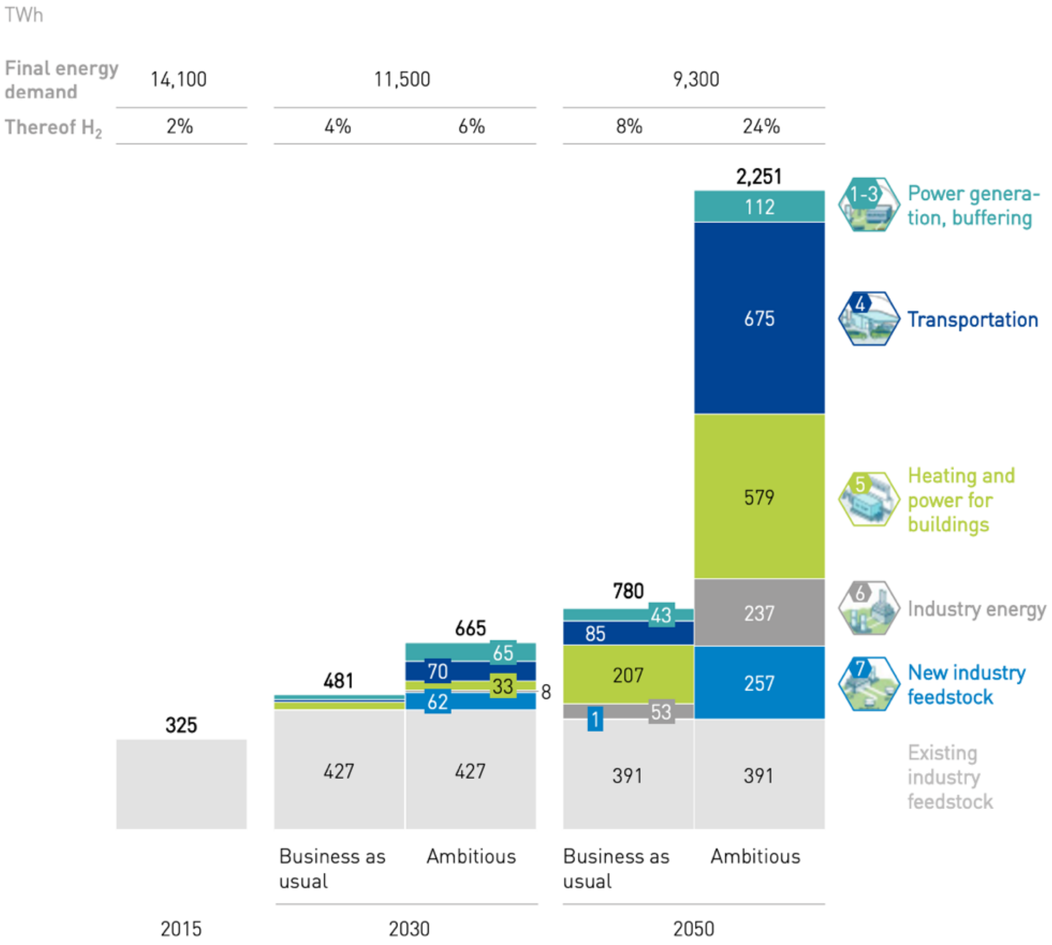


Figure 3. Different scenarios of energy demand and share of hydrogen by industries. (FCH JU 2019)

Major sectors for hydrogen utilisation are also building's heating and feedstock for industry. The estimated demand for hydrogen (FCH JU 2019) in the building sector could be up to 579 TWh in 2050. However, exploiting the great potential on large scale will most probably face several challenges, such as a lack of a hydrogen distribution network. In addition, FCH JU mentions the heating equipment that needs to be replaced for most of the cases by hydrogen boilers and fuel cells. On the other hand, replacing may not cause the most significant challenges due to quite a short lifetime of existing equipment (10-15 years). In addition to heating, hydrogen can be utilised as an electricity producer for buildings using fuel cells as a combined heat and power unit. The feasibility of such kinds of devices needs to be studied further before large-scale utilisation. Fuel cells and other modern furnaces convert fuel into heat with relatively high efficiency. However, air-source heat pumps which use outside air and electricity to produce heat are also feasible solutions. High coefficient of performance and the capability to act as a cooler or heater based on the need have increased the popularity of air-source pumps in areas where seasonal variations are noticeable.

Some industrial processes consume large amounts of electricity and produce a significant portion of regional CO_2 emissions. The EU member states are no exception in this case, and their industrial processes are also large CO_2 emitters. However, the use of green hydrogen could provide major mitigation in industrial CO_2 emissions. One of the most polluting processes is steel manufacturing, where hydrogen can be used, for example, instead of coke to remove CO_2 from the process. The possibilities are enormous due to the large steel production capacity in the EU. After China, the EU is the second-largest steel producer with an annual production of 177 million tons. (European Commission 2020a). Hydrogen demand per tonne of steel is 500 m^3 which corresponds to 1.5 MWh of energy. (Green 2018). In case that all steel production in the EU will use green hydrogen as a decarbonisation option in their processes, it would lead to 265 TWh of green hydrogen demand per year in steel production.

Hydrogen demand and consumption seem to be found primarily from the transportation sector, building's heating, and decarbonisation of the polluting industrial processes. In turn, as indicated in Figure 3, only a small share of green hydrogen demand is foreseen to go to the power generation sector (5 %). The following chapters focus on the deployment of hydrogen in electricity generation, its benefits and key challenges.

3.2 Use of hydrogen in electricity generation

Utilisation challenges of green hydrogen in electricity generation consist not only of technological issues. Competitiveness and costs are also affected by other factors, which are discussed in this section. The most significant benefits of green hydrogen in electricity generation are also reviewed. The competitiveness and profitability of green hydrogen can also improve through the various policy measures, which will be outlined in this section. As explained in previous chapters, there are several potential consumers existing for green hydrogen. Even if green hydrogen production is increased according to the EU's target to 665 TWh by 2030, there will be significant challenges to provide green hydrogen at an affordable price for all. This chapter will study the demand for green hydrogen in the electricity generation sector and analyse the required growth in renewable electricity generation.

3.2.1 Demand in electricity generation

Figure 3 indicates that electricity generation will be the industry with the lowest hydrogen demand in business as usual and ambitious scenarios in 2050. For the electricity generation, there would be only 112 TWh of demand for hydrogen in 2050 in the ambitious scenario, which corresponds to about 1.2 % of total energy demand in the EU.

Comparing the figures, it is visible that the share of hydrogen in electricity generation is relatively small. As further proof of this, required energy in electricity generation could be viewed. For instance, in 2018, electricity generation consumed about 151 TWh of fuel resources in Finland (Stat 2019). According to Figure 3, the share of hydrogen demand in the electricity generation sector would be about 2.7 % of the European

Union's hydrogen markets. If it is assumed that the demand for hydrogen in Finland would be distributed in the same way as in the EU, there would be demand for only 3 TWh of hydrogen in electricity generation in Finland. Compared to the Finnish fuel used for electricity generation in 2018, the approximated demand for hydrogen would match only a 1.9 % share of electricity generation energy needs.

As reported by FCH JU (2019), the power generation and sector of transportation emits approximately equal amounts of CO_2 emissions annually. However, it is shown in previously presented Figure 3 that by 2050 hydrogen will be used six times more in the transportation sector than in the power generation. Although the need for emission reductions is equal, analysis shows that the transport sector seems to be a more attractive option for clean hydrogen. Such an assessment can be partly explained by the matter that the transport sector aims to exploit green hydrogen, especially in heavy road vehicles, which cause a significant share of transportation emissions.

In electricity generation, clean hydrogen cannot be burned in coal-fired plants, which are the most emitting power generation options. The utilisation of green hydrogen in electricity generation is otherwise challenging, as in several cases hydrogen would have to be transported to power plants along pipelines. Usually, construction is a slow and expensive process, especially for remote power plants. One reason for the potentially low green hydrogen demand in electricity generation in the future can be considered to be an extremely low experience in the use of hydrogen compared to other sectors. For example, current hydrogen consumption within the EU is mainly related to the chemical industry (63 %) and refineries (30 %) (Jovan & Dolanc 2020). In the light of this information, it may be inevitable that sectors where hydrogen is already utilised for several years, will also have the highest green hydrogen consumption.

In contrast, according to the 2020 gas report released by International Gas Union, BloombergNEF, and Snam, the power generation sector could gain over 30 % of total hydrogen use globally in 2050. Strong policy actions and a large-scale hydrogen network are required in this result. According to the report, power sector would gain a much bigger share of hydrogen consumption than estimated in the European Commission's hydrogen strategy. This could be partly explained by the fact that the global gas report supposes hydrogen's price to be 0.9 € per kilogram to large consumers and 3.6 € per kilogram to road vehicles. In that case, demand for green hydrogen is lower in the transportation sector due to higher prices.

In Figure 4, it is visible that the strength of the policy will strongly affect the competitiveness and demand for green hydrogen. With a weak policy, the demand will maintain a low profile in all sectors except transportation. However, this assessment is from the global perspective and needs to be taken into account when observing the magnitude of the values. It is not recommended to compare global and European results together because in a global scenario, all countries are considered, including those that have no access to gas networks and relatively cheap gas.

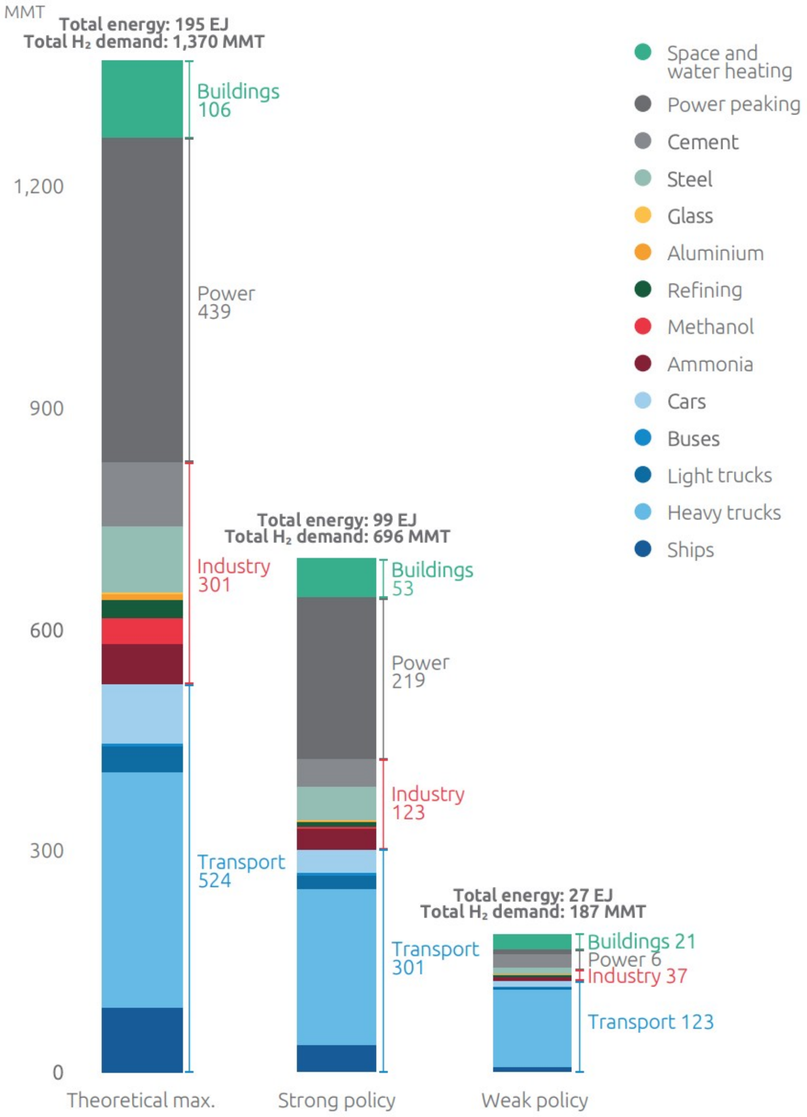


Figure 4. Different green hydrogen demand scenarios by 2050. (Snam, IGU & BloombergNEF 2020).

3.2.2 Expanded need for renewable hydrogen

In electricity generation, the problem with the use of green hydrogen is also the inefficiency of energy shifting. This will result in a situation where an enormous amount of renewable surplus energy has to be produced. The required amount of renewable energy depends on how hydrogen is to be used in electricity shifting. Some processes require a greater amount of renewable energy but may have other benefits. The following diagram, Figure 5, shows a review of three different options for hydrogen use in electricity generation. The first option is to utilise hydrogen produced via electrolysis for the methanation process and then use the generated methane in power shifting.

The second option is to combust pure hydrogen in an internal combustion engine. Since options one and two both are using ICE as a power source, the contribution of methanation to the total power shift can be observed. The third option in this comparison is to feed renewable energy produced mainly from wind and solar sources to the electrolysis process and then regenerate electricity by using fuel cell technology. The efficiency of electrolysers was evaluated based on the previously mentioned IRENA (2020) and the fuel cells' efficiency based on the fact sheet released by the U.S. Department of Energy (2015).

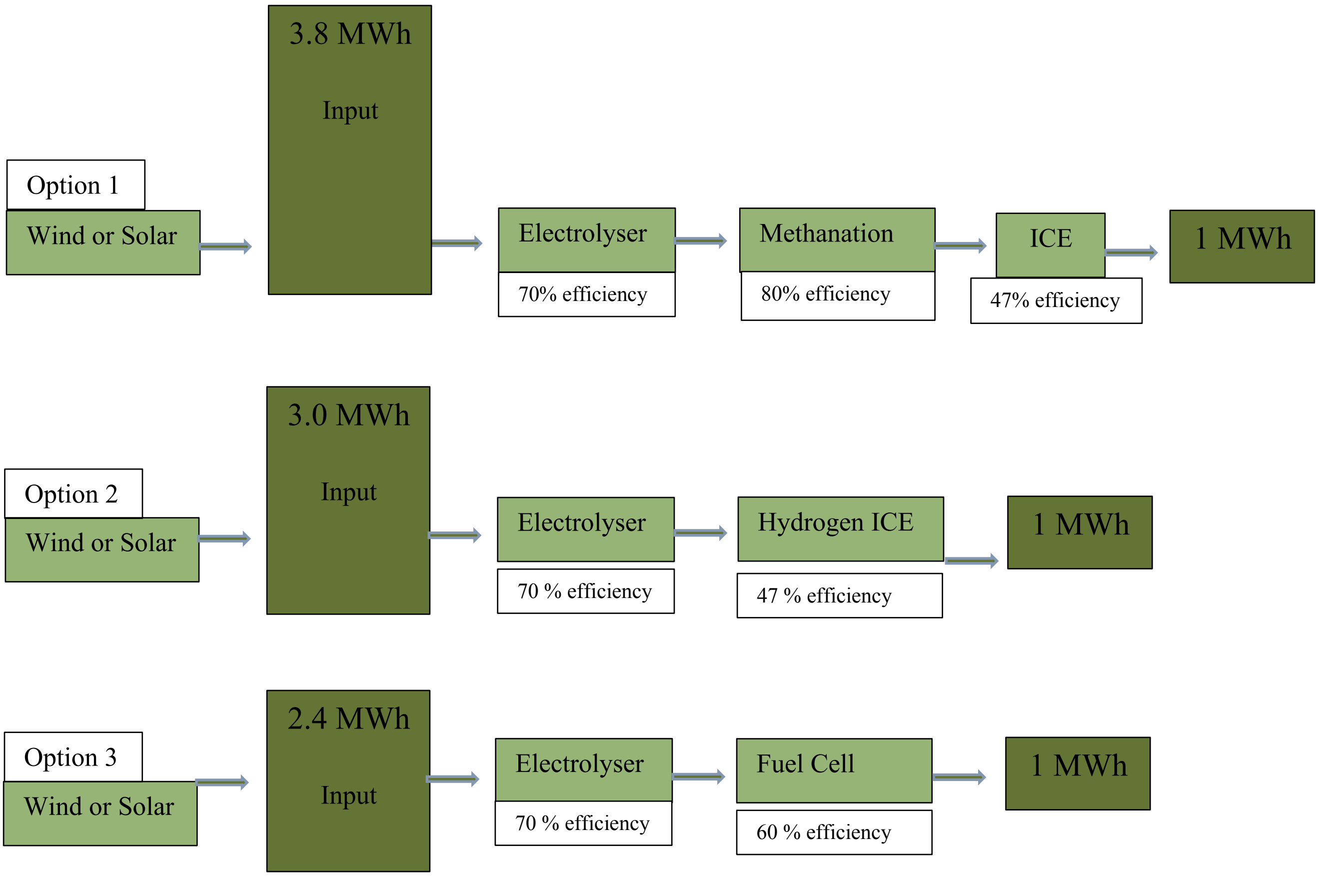


Figure 5. Three hydrogen utilisation options in electricity shifting. (IRENA 2020: U.S. Department of Energy 2015).

An expanding demand for renewable energy may cause problems when growing the hydrogen market. For instance, in the first option, 2.8 times more input electricity is required than the output of the process generating electricity. The most significant development in this figure will most probably be the improvement of the electrolysis process. The development of electrolysis is driven by the fact that this technology is needed whenever green hydrogen is produced. The EU’s hydrogen strategy estimates €24 – 42 billion of investment in electrolyser technology by 2030. International Renewable Energy Agency (IRENA) has stated in 2018, that Alkaline (ALK) electrolysers can achieve up to 68 % LHV-based efficiency by 2025, and PEM electrolysers, which are more flexible and environmentally friendly can achieve the 64 % efficiency by 2025 (IRENA 2018).

One optimization solution to reduce energy losses is to strive to implement the whole energy shifting process as close to the final consumer as possible. The ideal situation would be achieved if all parts of the processes could be executed in the same location. Renewable energy production, electrolysis process, hydrogen storage, power plant, and final consumer close to each other would result in the lowest possible losses in the process. If large amounts of renewable energy have to be fed into the electricity grid, it can destabilize the grid's balance. If the distance between electrolyser and fuel cell is long, a hydrogen pipeline is required, which causes significant additional costs. If electrolysers are connected in an off-grid system, electricity network-related charges and taxes can be avoided. Still, at the same time, their utilisation rate will be lower than 100 % due to the nature of renewable resources. (IRENA 2018).

3.3 Profitability in electricity generation

The technologies listed above strive for the best possible profitability in the use of hydrogen. The profitability of green hydrogen in electricity generation is affected, for instance, by the cost development of feedstock and the technology itself. The price of electricity strongly influences the cost of green hydrogen. The competitiveness of green hydrogen is enhanced by an increase in the carbon price, a strong political action to control climate change. The purpose of this section is to examine the prospects for the profitability of green hydrogen based on various analyses by several research companies and global agencies. The main focus is the profitability from the electricity generation point of view and the price development of green hydrogen.

3.3.1 Cost of green hydrogen

The costs of green hydrogen in the future are key factor that determine its profitability and success. If cost cannot be reduced in line with targets, deployment of green hydrogen on a large scale will be remarkably challenging. According to the European Commission's hydrogen strategy (2020), the cost of green hydrogen is currently between 2.5 – 5.5 €/kg depending on, for instance, what kind of energy source is used. The IEA agrees and estimates that the cost of green hydrogen is 3.5 – 5 €/kg. It corresponds to EUR 0.10 - 0.15 per kWh. In turn, the cost of natural gas for non-household consumers was EUR 0.03 per kWh in 2018 in the EU. According to the estimates mentioned above, the price of natural gas is over four times cheaper than green hydrogen. The highest natural gas prices among the EU member states are in Finland (0.06 per kWh) and France (EUR 0.04 per kWh). (Eurostat 2020a). The competitive situation between natural gas and green hydrogen will be explored further in Chapter 5.

There is also a clear difference in production costs between green and grey hydrogen. The cost of fossil-based hydrogen is around 1.5 €/kg, so in some cases, green hydrogen can cost over 3.5 times more than grey hydrogen at the moment. Different objectives of green hydrogen costs reduction have been published in other sources. Research company Wood Mackenzie has stated that the cost of green hydrogen production could fall by 50 % by the end of this decade. This appraisal does not take into account the cost development of transportation and storage. The significant expense of green hydrogen is the cost of the electrolysis process. Over the past ten years, electrolyser costs have dropped by 60 %, and a further 50 % reduction is estimated to occur by 2030.

BloombergNEF stated in the global gas report 2020 that the PEM technology cost has decreased even 50 % from 2.5 €/W to 1.25 €/W just in five years. As mentioned in the previous chapters, Germany aims to be a leader in the hydrogen economy. However, BNEF and IRENA publications indicate that China has clear superiority over other countries from the cost perspective. For instance, in the best case, alkaline electrolyser Capex cost in China is currently around 0.18 €/W while the Capex of Western-made alkaline electrolysers were 1.1 €/W in 2019 (Snam, IGU & BloombergNEF 2020). In addition, BNEF estimates that the Capex costs could be reduced even lower, around 0.10 €/W by 2030 in China. In turn, based on the IEA, the lowest Capex for the alkaline electrolysers would be around 0.45 €/W currently. (Deutsch & Graf 2019). Consequently, IRENA and BNEF agree on the current level of alkaline electrolyser costs, while IEA considers the costs higher in China. The costs of green hydrogen production need to be reduced in the short term. According to the European hydrogen strategy, the price of green hydrogen is expected to drop around 1.1 – 2.4 €/kg by 2030, which corresponds to a 56 % decrease in green hydrogen production costs. (European Commission 2020b).

The profitability of green hydrogen is also affected by the price development of other energy sources. The most critical factor is the electricity price used for the electrolysis process. In the global gas report, BloombergNEF estimates the cost of green hydrogen in 2030 and 2050, and the results are visible in Figure 6. Large-scale production processes and optimal Capex costs were used as an assumption. This optimistically constructed study shows that green hydrogen could become a competitive option as early as 2030. Another observation is that the cost range of green hydrogen will decrease in the future. Currently, the production cost of green hydrogen varies significantly, partly explained by different production conditions and volumes. It needs to be considered that this compares green hydrogen with low-carbon hydrogen. If green hydrogen were compared to grey hydrogen (without CCUS), renewable options become competitive in later stages. The left-side Y-axis shows the price per mass unit, and on the right, the cost is presented by the price per energy unit.

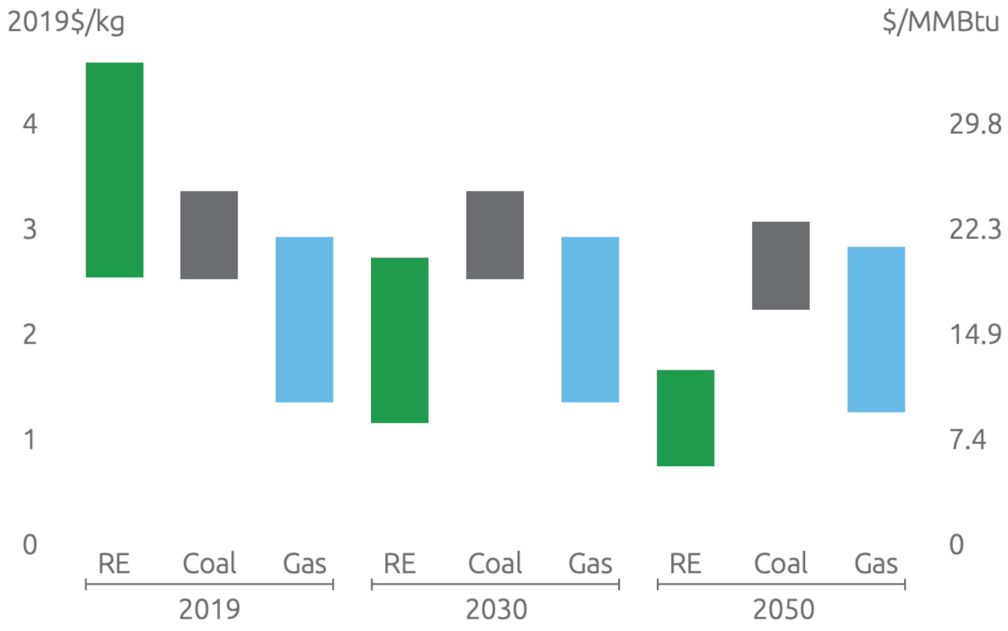


Figure 6. Estimated levelized cost of green hydrogen (RE) and low-carbon options produced from Coal and Gas. Research is done by BloombergNEF. (Snam, IGU & BloombergNEF 2020). ($/MMBtu can be converted into €/MWh with a conversion rate of 1 $/MMBtu = 0.29 $/MWh = 0.26 €/MWh)

In turn, Adam Christensen (2020) has assessed the development of green hydrogen prices in a completely different way compared to the report by the IEA and the European Commission. The International Council of Clean Transportation funds that particular research paper, published in June 2020. The publication also criticises the report published by BNEF in that the price of green hydrogen could fall to 1.25 € - 2.6 €/kg. According to Christensen, BNEF is ignoring many system costs required in hydrogen production and focuses only on prices caused by electricity and water. This research has addressed the developments for costs of green hydrogen in the US and Europe.

In case that the electrolyser is directly connected to the renewable source and the price of onshore wind is approximately between 30 – 50 €/MWh, Christensen estimates that green hydrogen could be produced at the minimum cost of 2.58 €/kg in 2030. Considering regional differences in the price of renewable energy, the paper estimates that the median price of green hydrogen in 2030 could be 13.14 €/kg. Although these results are more conservative and other studies disagree with them, one important note is that hydrogen prices generally used in the IEA and EU reports can only be achieved under ideal conditions. The result from Christensen's study is presented in following Figure 7. Further review for the green hydrogen prices is done in Chapter 5.

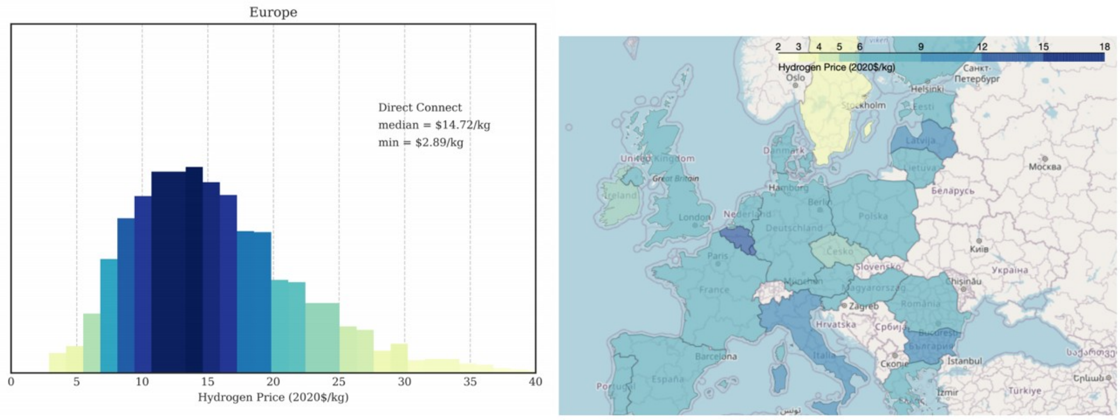


Figure 7. Green hydrogen price in Europe in 2030. (Christensen 2020)

3.3.2 Price of electricity

As mentioned, the development of electricity and carbon price will have crucial impact on the profitability of green hydrogen. The ideal situation is achieved when electricity prices are low, and carbon prices are high. Low electricity price gives affordable hydrogen via electrolysis, and high carbon price would increase the expenditures of competitors and improve hydrogen's cost-competitiveness. The cost of electricity produced in the EU via wind turbines can vary a lot. In 2019, the average grid price of wind energy was 35 €/MWh in Germany and 64 €/MWh in Italy. (Statista 2020). Momentarily lower prices are already being reached in certain areas and scaling up production will continue to lower costs.

As reported by Simon Flowers, the economics of green hydrogen would work with the electricity price below 27 €/MWh. Due to extensive price differences between the countries, it would be essential to produce renewable electricity where it is profitable. Significant developments are already taking place; for example, the cost of offshore wind energy has fallen about 50 % in the last five years. Senior research analyst of Wood Mackenzie, Ben Gallagher, has stated that the cost of green hydrogen production could fall about 64 % by 2040 and make it cost-competitive with fossil-based hydrogen if electricity price remains low and facilitates this transition. In addition to this, the load factor of green hydrogen plants with renewable source should reach 50 %, while currently, it is around 20 %. (Flowers 2020). Plants are not profitable at utilisation rates of this level but need to be increased. The lack of components required in the production and low demand for green hydrogen diminishes the plant's load factor. Reflecting on above mentioned costs, three different scenarios for electricity prices are used to evaluate the production costs of green hydrogen in Chapter 5.

3.3.3 Carbon prices

An emissions trading system has been created to control greenhouse gas emissions in the EU. The basic idea is that emissions produced must have the corresponding amount of emission allowances, the price of which is determined by trading on a market as other financial instruments. The most commonly traded emission is carbon credits, which define carbon price in units of €/CO_2ton. The magnitude of the carbon prices affects the feasibility of green hydrogen. Over the years, carbon prices have fluctuated heavily, and in February 2021, the price climbed up to an all-time high of 40.19 €/ CO_2ton (Watson 2021). The European Union has recently increased the Linear Reduction Factor (LRF) from 1.7 % to 2.2 %. In this case, LRF means that the cap on the total number of allowance quantities decreases linearly. (Bruninx, Ovaere & Delarue 2020). It is an indicative signal of the future development direction.

Assessing carbon price developments is highly complex due to numerous affecting factors. Several different parties have assessed of the future carbon prices and how high the price needs to go for cleaner energy sources like green hydrogen to become competitive. The European Commission published its new climate ambition in September 2020 and set the target to a 55 % cut in greenhouse gas emissions by 2030 compared to the 1990 level. In the report, multiple future scenarios are presented where carbon prices range from 32 €/ton to 65 €/ton. (European Commission 2020c). The Zero Carbon Commission has called the UK to raise carbon price to 61 € per tonne by 2025 and 83 € per tonne by 2030. (Edie 2020). Despite the increase in carbon pricing in 2020, it is estimated by the participants of the carbon market that the coronavirus will lower prices for a couple of years. As stated in the study by PwC, the average ETS price for the period 2021-2030 is estimated to be 31.71 €/CO_2ton while it was 36.05 €/ CO_2ton a year ago. (IETA 2020).

The European hydrogen strategy estimates that 55-90 €/CO_2ton is required to make blue hydrogen competitive with fossil-based hydrogen. The Financial Times released an article in August 2020 where the needed carbon price levels to make green hydrogen feasible against grey hydrogen in 2030 were evaluated. It was considered that if green hydrogen could be produced via electrolysis in the price range of 2-2.25 € per kilogram, a price of approximately 79 € - 102 € per tonne of carbon would be required. Also, the report states that a new pricing model for carbon could be in the pipeline. From their perspective, the cost of green hydrogen could become the crucial parameter of the new pricing model. (Lewis 2020). Also, higher estimates of the required carbon price have been presented. The required level depends on the price of gas or coal at which the grey hydrogen is produced.

Overall, carbon prices need to be ramped up if green hydrogen desires to be competitive against low-cost fossil fuels. The same issue has been studied and observed in the global gas report as well, and Figure 8 shows the key results. The outcomes pointed which sectors cause the most significant CO_2 emissions annually and how high carbon price is needed to make the green hydrogen feasible in a specific industry. Power generation via gas solution is one of the largest CO_2 producers, and carbon price needs to be multiplied by the current level to make green hydrogen competitive.

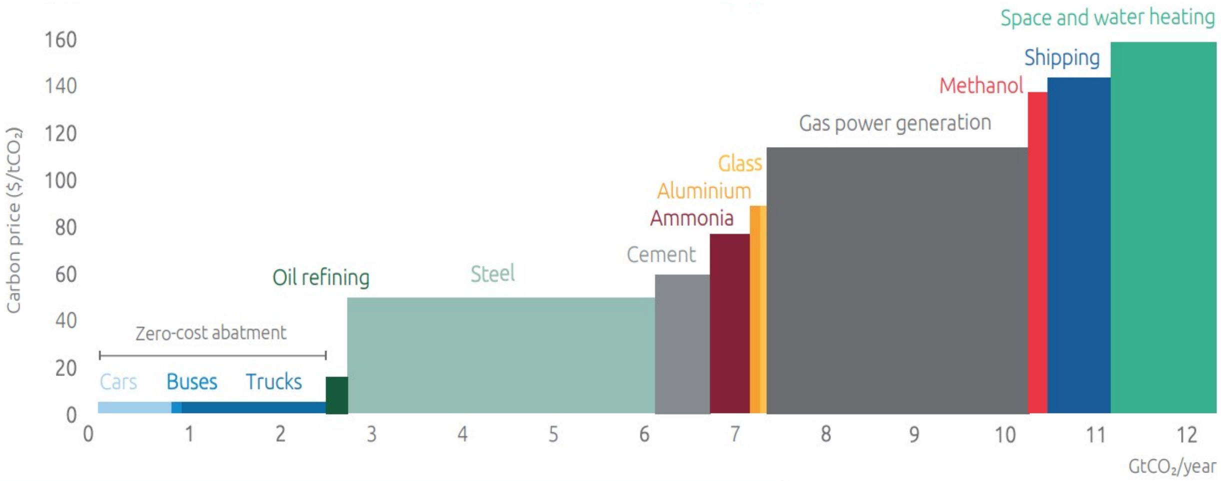


Figure 8. Required sectoral carbon prices to make green hydrogen (0.9 €/kg) competitive against low-cost natural gas. (Snam, IGU & BloombergNEF 2020).

3.3.4 Feasibility of green hydrogen in intense competition

The basic idea behind using green hydrogen in electricity generation is that renewable energy is converted to hydrogen via the electrolysis process and then regenerated back to electricity. The main advantage of this process is that surplus energy from renewable sources can be fed into the electrolysis process, and hydrogen can be used in power production when demand is higher. In this way, a balancing power system is possible, and surplus energy can be utilised. In electricity generation, the most substantial competitor gas to green hydrogen is natural gas. Additionally, batteries can efficiently convert chemical energy into electrical energy and operate as short-term energy storage. However, batteries cannot store a large amount of energy for a long period, such as weeks or even seasons. Therefore, long-term energy storage is the potential market for green hydrogen.

For the electricity producers and all of the closest stakeholders, it is valuable to recognize when green hydrogen becomes competitive with natural gas. One particular study done by COAG Energy Council Hydrogen Working Group in Australia in 2019 looks at the cost of using hydrogen compared to alternative technologies in 2030. Results can be seen in Figure 9. It needs to be recognized that the study was done in Australia, and there may be some differences in production capacities and costs. The results, however, show that the breakeven point in the cost of hydrogen against alternatives can be achieved at different times in different sectors. According to this study, the price of green hydrogen would be around 1.7 - 2.5 €/kg.

Green hydrogen would be most competitive in the transport sector when compared to the battery electric vehicles, especially in heavy duty solutions. This argument is also supported by the 2020 Global Gas Report, which estimates that hydrogen-powered fuel cell trucks will become more cost-effective than conventional diesel in 2031. At these price levels, green hydrogen would not be cost-competitive in light blue bar sectors. As it is noticeable, the cost of green hydrogen is estimated to be twice as much as the cost of natural gas in power generation. Cost reduction should still be able to make for cost-competitiveness. The results would be slightly different if the comparison would be done between other energy sources.

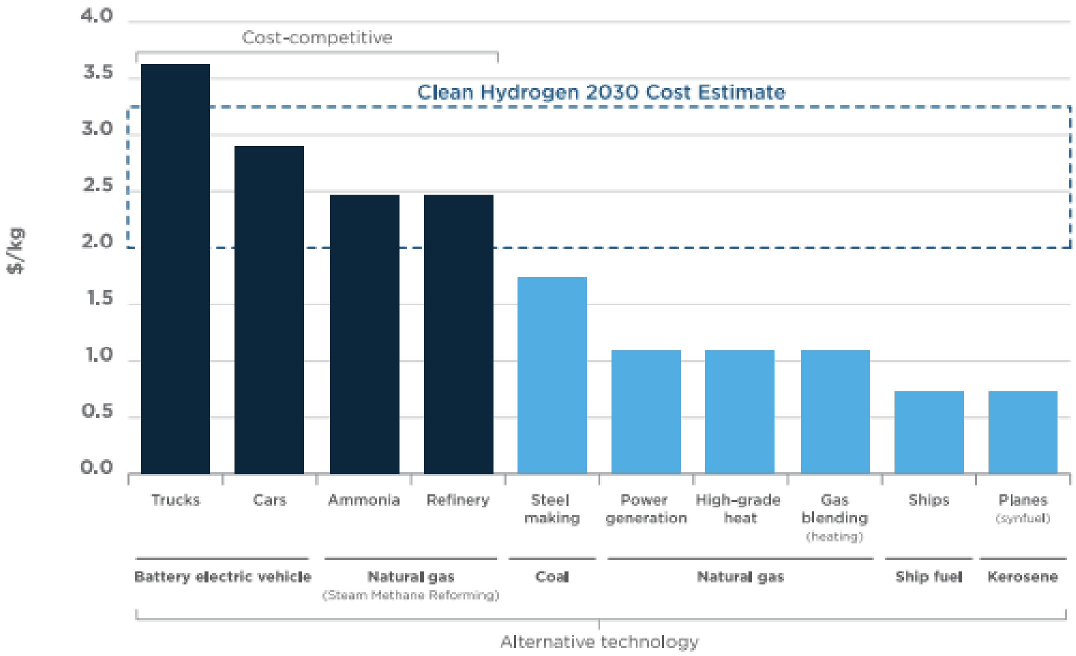


Figure 9. Estimated cost of green hydrogen in 2030 and cost-competitiveness against different options. (COAG Energy Council 2019)

It can be seen that green hydrogen will face stiff competition against natural gas for the market share. It is not straightforward to assess when green hydrogen competitiveness breakeven against natural gas will be achieved. In addition to the price development of green hydrogen, natural gas's price is expected to increase in the future. The issue that needs to be addressed in the gas conversation in the EU is the dependency on imported gas. Based on Eurostat (2020b), natural gas dependency in the EU reached its all-time high of 89.5 % in 2019. Russia is the largest single natural gas importer with 40 % of total natural gas imports in the EU. (Eurostat 2019). The volume of energy imports in Europe is enormous, and it has increased over the recent years. Better energy self-sufficiency is generally believed to improve national security and regional economy. If green hydrogen can be produced locally in Europe and it can partially displace the needed amount of natural gas, it could reduce the energy dependency in Europe.

The same form of power generation can produce electricity for several different uses. The solution can generate electricity as a baseload or instead as a peaking unit designed to balance fluctuations in the electricity markets. When the number of renewables is increasing, clean, load-following power plants are needed. The peaking units' purpose is to generate electricity during consumption peaks, and one of the most important features is a quick start and ramp-up time. The Hydrogen Council published a report in January 2020 on the cost competitiveness of hydrogen. Based on the study, it can be seen that only fuel cell backup generators and combined turbines would be competitive in a group of low-carbon applications in electricity generation. However, those solutions would not be cost-competitive compared to conventional sources. The results are visible in Figure 10.

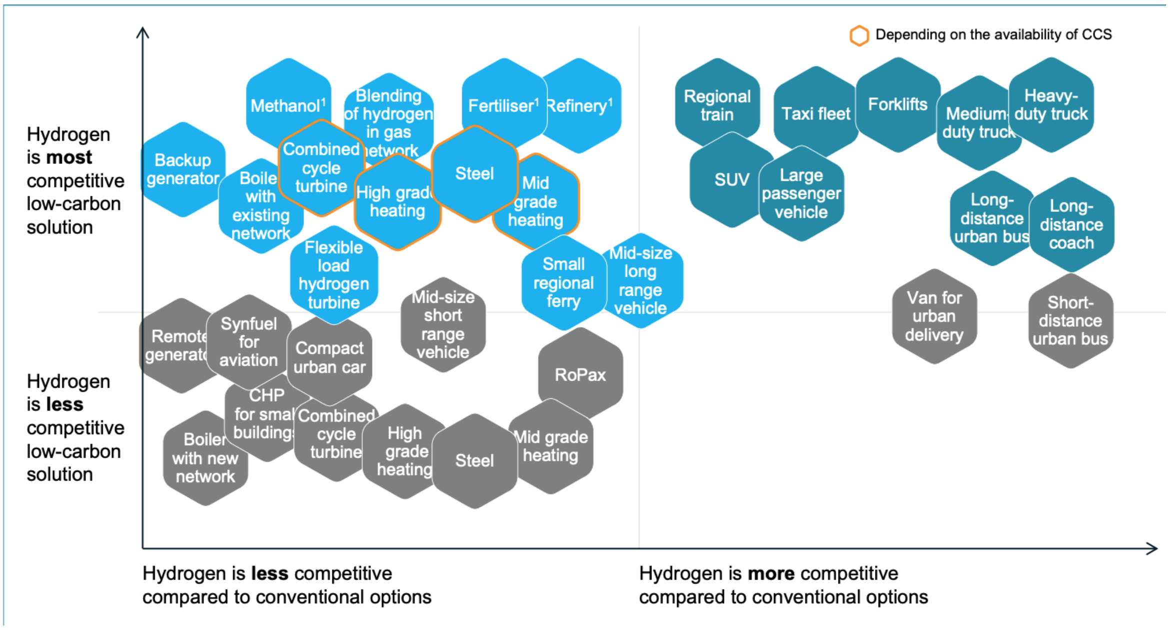


Figure 10. Hydrogen profitability comparison in different sectors. (Hydrogen Council 2020).

4 Pipeline transportation and storage

Hydrogen can be transported in numerous ways, but at the same time, transportation is one of the critical challenges of the hydrogen business. Hydrogen can be transported via trucks or ships in the form of pure gas or liquid. However, as stated in several research pieces, hydrogen transported in large volumes in the pipeline has been seen as the most cost-effective way. According to the European Commission hydrogen strategy, to facilitate a well-functioning hydrogen market, potential users need to have incontinent hydrogen access. (European Commission 2020b). This chapter will cover pipelines as a transportation method of green hydrogen. Hydrogen networks could be converted from the existing natural gas pipeline, or completely new infrastructure for hydrogen could be built. In addition to these options, hydrogen can be blended with natural gas.

4.1 Existing pipelines

Europe has one of the most comprehensive gas networks globally, with 2.2 million kilometres of the gas pipeline inside the continent. (Hydrogen Europe 2019: 4). In practice, all operating networks are built for the use of natural gas. For green hydrogen to become the main decarbonisation option in the EU, it needs to transport in large quantities cost-effectively. Under the current circumstances, the existing natural gas network could be utilised to grow the green hydrogen markets in the EU. Minor changes to the current natural gas network would be required if green hydrogen were used in the power-to-X process to produce synthetic methane. In the process, electricity is generated by renewable energy sources, used to separate hydrogen from the water via electrolysis, CO_2 is captured from the atmosphere or straight from the industrial processes, carbon is combined with hydrogen and various synthetic fuels such as methane (CH_4) can be created. The most significant feature of synthetic methane, in this case, is that it can be fed directly into the existing natural gas network without remarkable changes in infrastructure. A Disadvantage of synthetic methane is that the shifting process's efficiency will decrease due to methanation, as observed in Figure 5.

In the second option, clean hydrogen is blended with natural gas in a specific ratio. The European Union member states have individual national limits on how much hydrogen can be blended with natural gas. For instance, in Finland, the limit is 1 % by volume, while in France, the limit is 6 %. (IEA 2020). When hydrogen is blended with natural gas, only some latest modifications to the infrastructure are required.

Several different standpoints have been expressed on the benefits of hydrogen blending utilisation. As stated by the CEO of the Italian energy infrastructure company Snam, hydrogen blending is a smart way to extend the production and utilisation of hydrogen. They have successfully tested the world's first hydrogen blend, a natural gas network-designed turbine, in July 2020. Globally, Snam is operating over 41,000 km of the natural gas network, and they have announced that about 70 % of its Italian network is ready for hydrogen blend already today. The tested turbine by Snam is designed to run a blend of up to 10 % hydrogen. (Snam 2020). One of the main advantages is that hydrogen blended with natural gas can reduce CO_2, carbon monoxide (CO), and hydrocarbons (HC) emissions. On the other hand, hydrogen use could increase nitrogen oxide emissions, and studies have shown that CO_2 reduction is relatively low. According to the calculations, blending 10 % of hydrogen into the total gas capacity operated by Snam would lead to 5 million tons of CO_2 reduction per year (Snam 2020).

For internal combustion engines, it has been explored that 20 % of hydrogen in the gas mixture is ideal for achieving the best possible engine performance and low emissions at the same time. When the portion of hydrogen increases, the temperature of exhaust gas rises, creating an ideal condition for the formation of NOx emissions. Due to the high flammability of hydrogen, safety concerns also set their limits for the mixture. Studies have estimated that blends below 20 % have only a minor risk for ignition. The leakage rates of hydrogen could be 3-4 times faster than methane through the sealing materials (Melaina, Penev, Steward, Antonia, Bush, Daniel, Heimiller & Melius 2012).

The blend can be considered to decreases the value of hydrogen. And it also affects the quality of gas used in Europe.

The load factor is not high level across the existing gas network, and therefore the utilisation rate of a certain distance of the gas network could be too low. This kind of natural gas pipeline status offers an opportunity to adapt the existing network to suit 100 % pure hydrogen. Some European countries have already taken actions towards the green hydrogen gas network.

Germany announced in March 2020 that it would build the first 130 km of green hydrogen pipeline by 2022. (Radowitz 2020a). Also, Germany is planning to build 1,200 km by 2030. Up to 1,100 km of the hydrogen network is planned to be converted from the existing gas network. Total costs of the new grid are estimated to be around 600 million euros which mean about 500 k€/km. One of this new grid's main objectives is to facilitate a climate-neutral future for steel and chemical industries. Germany's gas grid operator's association has already announced the plan for a 5,900 km hydrogen network, and this would be implemented by using the existing infrastructure 90 %. (Radowitz 2020b). It gives a strong signal that the utilisation of existing gas networks will play a vital role in green hydrogen infrastructure.

From an electricity generation perspective, transportation is one of the key factors for success. It is almost impossible for electricity producers to access the necessary amount of hydrogen without connecting to the gas network. Based on published strategies, existing natural gas pipelines with hydrogen conversion are seen as the most feasible option, at least in the initial phase.

4.2 New pipeline infrastructure

The cost of the new hydrogen pipeline infrastructure is highly challenging to estimate due to several price-influencing variables. However, the most significant single factor is the size of the installed capacity. The nature of the hydrogen imposes additional requirements for the used materials. For instance, a commonly used material in natural gas networks is carbon steel which is not suitable for the pure hydrogen pipeline because of the embrittlement of steel material. The effect of hydrogen on materials is one of the key research topics for scientists. (Elaoud, Hafsi & Mishra 2018). The fibre-reinforced polymer (FRP) is presented as one solution for the material of hydrogen pipeline. The installation cost of FRP could be about 25 % lower compared to the conventional pipelines (Rawls, Ronevich & Slifka 2017).

Additional welding procedures and testing for gas leaks need to be considered when using hydrogen instead of natural gas, and those cause additional costs. There are also other research results available on the use of steel materials in hydrogen transport. The National Institute of Standards and Technology (NIST) has studied the durability of various steel products and ended up with results that high-strength steel models like X70 with a thickness of 0.375 inches (9.53 mm) do not have a high risk for fatigue crack. (NIST 2015). The European Hydrogen Backbone (2020) report states that only minor changes are required to convert the existing network to hydrogen. According to the report, pipeline materials are generally the same, and the main modifications are nitrogen purging, crack identification equipment, and valve replacement. These modifications are estimated to cost about 10 – 25 % of the new hydrogen pipeline. (Buseman, Peters, van der Leun & Wang 2020).

Moreover, rights of way (ROW) are needed when a new pipeline is constructed. ROW is the right for land use, which will increase the pipeline's total capital costs. Based on pipelines built in the past, it could be estimated that the cost of ROW would be around 6 – 10 % of the total infrastructure cost. (Menon 2015). Researchers from NIST have examined in 2015 the potential cost of a hydrogen pipeline and stated that it is more expensive than other types of gas pipelines. Depending on the dimension of the pipe and other factors, it has been found that the cost of a hydrogen pipeline network could be up to 68 % higher than a natural gas network. As stated by Professor Van Wijk (2019), large-scale pipeline projects have shown that the average cost is 1 million € per 10 Gigawatts per kilometre. However, costs vary a lot by region, and the large-scale construction of hydrogen networks will most probably face some unpredictable challenges in the future. Also, Professor Van Wijk estimates that approximately losses 2 % could be taking place in hydrogen transportation. That value is used in the calculations in Chapter 5.

In addition to Germany, the EU has also released its targets to build an extensive hydrogen network in Europe. According to the report supported by Guidehouse and published in July 2020, construction of the European hydrogen backbone would be completed by 2040, including 23,000 km of hydrogen pipelines. By 2030, around 6,300 kilometres of hydrogen network in Europe, mainly converted from the existing natural gas network. By 2040, it is estimated that 75 % of the European hydrogen network would be converted from the natural gas network, and only 25 % would be a new hydrogen network. The designed backbone network in Europe for hydrogen is visible in Figure 11.

The backbone is connected to northern Africa via Italy and Spain. Eleven gas infrastructure companies have been involved in creating this report. These companies are located in ten different countries appearing on this map. Because not all European countries are involved in this initiative, some possible additional routes are marked with a dotted line only. In the case of hydrogen production in Africa, the idea would be to exploit the significant solar energy capacity in the Sahara Desert. In this way, competitive green hydrogen could be produced and imported into Europe. Further research about Africa's potential as a producer of green hydrogen is required but considering that opportunity is excluded from this thesis. Figure 11 also indicates possible storage locations for hydrogen, and those are discussed in the following chapters.

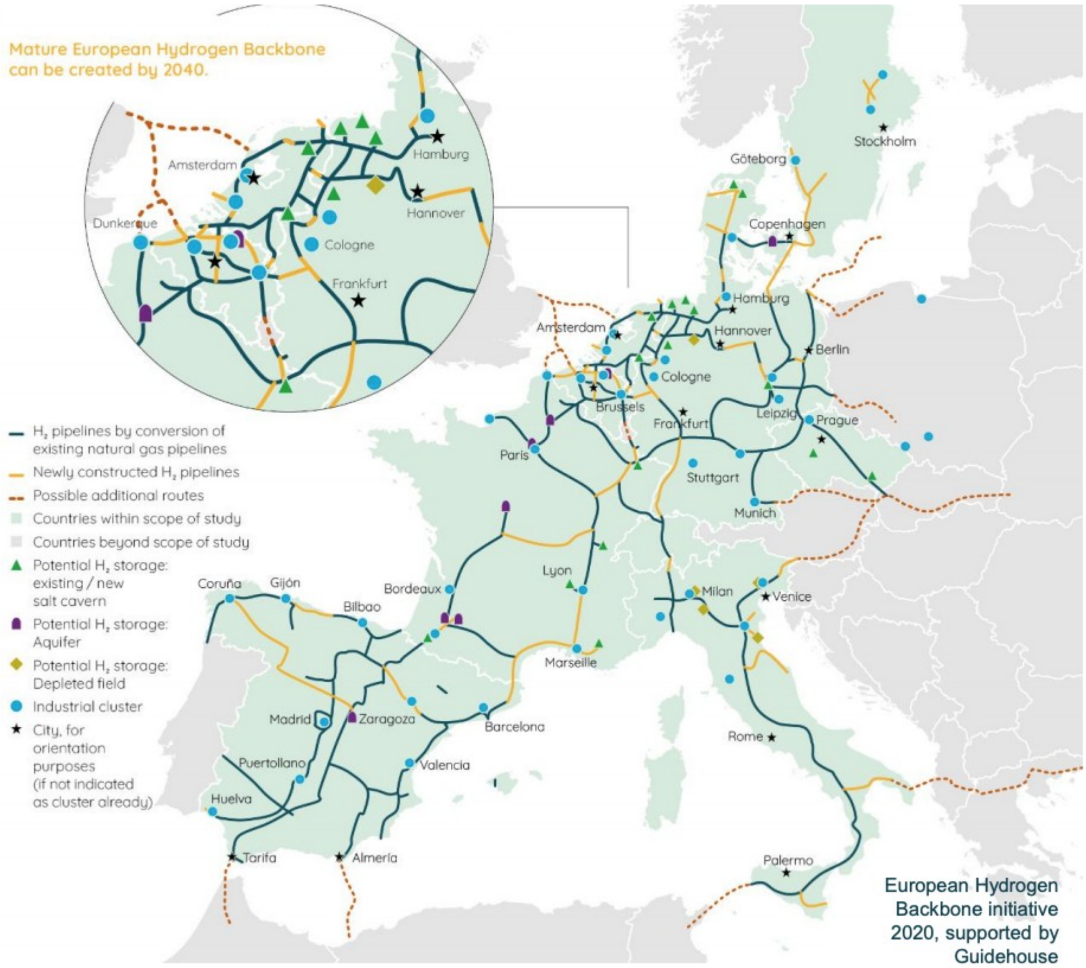


Figure 11. Plan for European hydrogen backbone. (Buseman, Peters, van der Leun & Wang 2020).

The construction of the new hydrogen network is the most significant single investment in hydrogen transmission. However, operating costs can rise high because, according to the Energy Technology Analysis (2014) by IEA, the energy required to maintain sufficient pressure can be as much as 10 – 15 % of transported energy. Compression costs consist of the price of electricity used for compression and the equipment investment itself. Therefore, the total cost, including capital and electricity costs, is estimated to be around 0.9 – 1.75 €/kg. (IEA 2014). These costs can be reduced via scaling up the hydrogen economy, and that is exactly what the EU is aiming to do. Also, IEA's study is already six years old, and not all factors are the same as they used to be. Most likely, the overall prices of compression are already lower when compared to the level of 2014. However, it is also estimated that compression requirements will increase between 2030 – 2040 due to significant transfer distances of the hydrogen.

Based on the European Hydrogen Backbone (EHB) initiative (2020), in the 2020s, the EU aims to utilise hydrogen blend with natural gas and start adapting the first natural gas networks to pure hydrogen. From the beginning of the 2030s, the intention is to begin the large-scale conversion of the natural gas network into hydrogen and at the same time build new pipelines. The supply chain of hydrogen is planned to be as follows:

1. Hydrogen is produced either from renewable energy sources or fossil-based fuels with CCS technology (green and blue hydrogen).

2. Transmission network including compression, metering, and distribution stations are constructed.

3. Storages have been utilised

4. Large industrial consumers use hydrogen directly from the gas network and other consumers through distribution stations.

The cost of this whole new infrastructure system is evaluated in the same EHB report. However, the accuracy and coverage of the cost estimation is rather insufficient. The transportation system's costs assessment varies on a large scale from 24 billion Euros to 64 billion Euros, while operating costs are expected to be 1.6 billion to 3.5 billion euros. In these scenarios, the load factor of the pipeline is assumed to be around 5,000 hours. The main explanations for the large range of cost estimates are several uncertainties such as the required capacity for hydrogen, the load factor of the pipeline and regional compression policies. Those factors need to be known for more detailed cost estimates. In general, the report states that the transportation costs are a relatively small portion of the total cost of hydrogen. Table 3 provides an apparent reason for the popularity of retrofitted pipelines. A hydrogen-ready pipeline can be built half of the price when using the retrofitted pipeline. Values in Table 3 are later used in Chapter 5 to present hydrogen transportation cost.

Table 3. Cost comparison of levelized cost of the new and converted infrastructure (European Hydrogen Backbone 2020).

		Low	Medium	High
Levelised cost, 100% new infrastructure	€/kg/1000km	0.16	0.20	0.23
Levelised cost, 100% retrofitted infrastructure	€/kg/1000km	0.07	0.11	0.15
Levelised cost, European Hydrogen Backbone (75% retrofitted)	**€/kg/1000km**	**0.09**	**0.13**	**0.17**

According to the European plan, the hydrogen backbone would consist of a 75 % retrofitted pipeline, while new infrastructure would present the share of 25 %. From Table 3, it can be concluded that a retrofitted option for hydrogen transportation is the most sensible solution in the light of costs. However, this estimate does not consider the amount of money spent in the past for the construction of the natural gas pipeline. Based on the first hydrogen transportation project, it has been possible to estimate that new infrastructure for hydrogen is quite similar to natural gas infrastructure. According to the EHB report, the costs of the new hydrogen network are about 10 – 50 % higher than the natural gas network.

4.3 Storage capacity in Europe

It is also desired to utilise green hydrogen due to its ability to store renewable energy. If surplus renewable energy would otherwise be wasted, it can be used to produce green hydrogen that can be utilised, for example, in electricity production at a later stage. In order to use hydrogen in electricity production when needed, a storage system for hydrogen is also required. Suppose the share of renewable energy production is significantly increased in line with international targets, the surplus energy will also be generated progressively and cause instability in electricity markets that need to be balanced by short- and long-term energy storages.

In the European Hydrogen strategy, the seasonal storage need for hydrogen is also identified. The main advantages of hydrogen storage are the rapid availability of hydrogen during demand peaks, assurance of hydrogen supply, and flexibility in hydrogen production. (European Commission 2020b). Hydrogen can be stored as a pressurized gas in vessels, underground facilities, or in the form of liquid. However, hydrogen must be cooled to -253 °C if the liquid form is desired. That would require a lot of energy, 0.2 % boil-off losses can occur, the process can be expensive; therefore, this option has not been seen as promising and effective. Continuous operation requires a large amount of hydrogen. In tanks and vessels, such quantities cannot store in, turning attraction into underground facilities. In this category, salt caverns, depleted gas fields, and aquifers storages are seen as possible options to store hydrogen. (Laban 2020).

Among different storage alternatives, salt caverns have been seen as the best storage option for hydrogen. In certain areas, the soil contains rock salt, which forms salt bed deposits. This formation can be exploited by drilling a hole and pumping water into the deposits, which will dissolve the salt. After the water is pumped out and an empty cavern is formed where, for instance, oil and gas can be stored. Salt caverns can form large storage capacity and are currently the most profitable way to store hydrogen. The pressure of hydrogen can be increased, but it will lead to higher risks like gas leaks, auto ignition, and hydrogen contamination. Naturally, hydrogen diffusivity is approximately three times larger than methane, so high-quality materials such as gaskets and pipes are required. To detect leaks, an extra substance, usually butanethiol, is added to natural gas to reveal the leaks. Challenge is that no light enough substance has been found for the same purpose when using hydrogen. Certain impurities can cause deterioration of hydrogen quality in salt caverns, one of which is the formation of hydrogen sulfide (H_2S). (Laban 2020).

One of the challenges is that rock salt formations are not discovered everywhere. Due to significant regional variation, there are no similar conditions for the hydrogen storage geographically. Since storage is considered one of the preconditions for the success of hydrogen, a site for hydrogen use needs to be chosen according to regional storage resources. The countries may have either onshore or offshore salt cavern capacities. For instance, in Europe, the most outstanding storage potential can be found in Germany, as shown in Figure 12 (Caglayan, Heinrichs, Kukla, Linssen, Robinius, Stolten & Weber 2020).

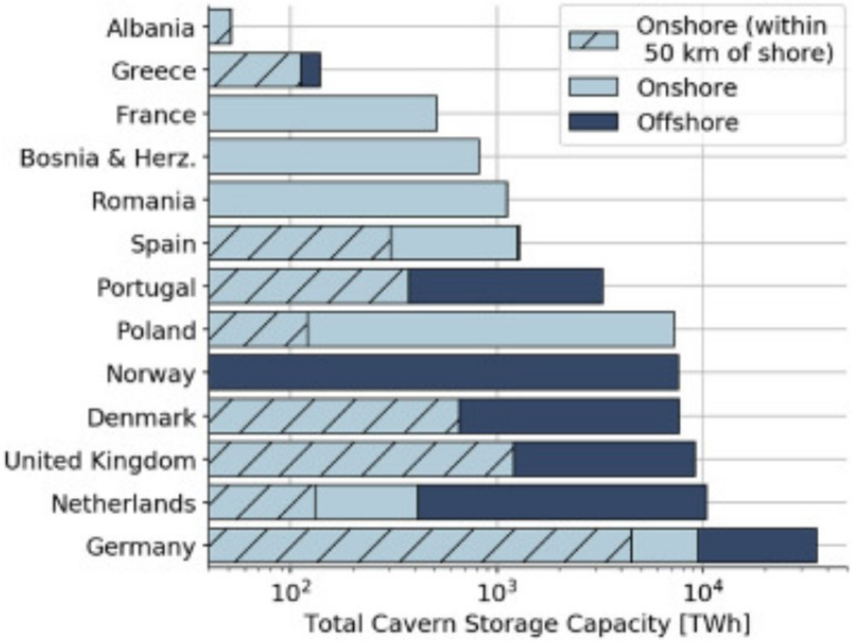


Figure 12. Cavern storage capacity per country (Caglayan et al. 2020)

According to Caglayan et al. (2020), the total cavern storage capacity for hydrogen in Europe is about 84.8 PWh. In proportion, this means that more than 127 times as much hydrogen could be stored in Europe as the EU's annual hydrogen production target is by 2030. If the European storage capacity is compared to the ambitious scenario for hydrogen production presented in Figure 3 (2251 TWh), the production target will represent about 2.6 % of the total storage capacity.

Costs of the salt caverns may vary due to several factors but, for instance, Gorre, Leeuwen & Ortloff (2018) have used the price of 0.11 €/m^3 for the salt cavern in their study. According to their research, a maximum of 280 kWh/m^3 of hydrogen can be stored. It means that the price per unit of energy for hydrogen storage is approximately 0.036 €/kWh. If this estimated cost is scaled up, hydrogen storage for the EU's 2030 target (665 TWh) would cost about 24 billion €. Also, Opex costs are estimated to be 2 % of Capex, which would mean annual costs of 479 million €. According to the master's thesis by Laban (2020), the total energy losses in hydrogen storage is about 3 %. This amount has also been used in the calculations in Chapter 5.

The energy sector's transition also brings the need for long-term energy storage, and salt caverns are the most suitable option to store hydrogen. More practical experience in using salt caverns is needed to overcome technological challenges and evaluate actual costs. Chapter 5 utilises the cost and efficiency estimates discussed in the thesis when calculating the total cost of the energy shifting process from renewables to gas and back to electricity.

5 Scenario analysis

The most significant benefit of green hydrogen in the electricity generation sector is the possibility of acting as long-term energy storage and therefore generating electricity during consumption peaks and improving the security of the electricity supply. The lower the price of “power-to-gas-to-power” shifting process can be achieved, the more of power plant capacity can be utilised. In this section, different scenario calculations were executed to identify and analyse the potential of green hydrogen in electricity generation from the perspective mentioned above. The results presented in this chapter are indicative. The complete shifting process is highly complex and includes many variables and not all the factors could be estimated in this thesis. However, the calculations aimed to take all of the relevant factors into account as thoroughly as possible.

5.1 Values and baseline scenario

This scenario analysis consists of three different configurations of variables to study each factor's effectiveness on the price of electricity produced via green hydrogen. In these scenarios, hydrogen production via renewables, hydrogen transportation, storage, and end-use in electricity generation are included. The following lists show the values that remain the same in all scenarios and changing parameters. Also, due to the intention to keep the calculations simple, ignored factors are presented in the third list.

Constant values:

1. Electrolyser Opex = 0.17 €/ kgH_2 (Assumed figure)
2. Transportation losses of hydrogen = 2 % (Van Wijk)
3. 1 kg of hydrogen = 33.33 kWh
4. Storage losses = 3 % (Laban)
5. Fuel cell Opex = 0.17 €/ kgH_2 (Assumed figure)

Changing parameters:

1. Price of electricity (€/MWh)
2. Electrolyser efficiency (%)
3. Transportation LCOH (€/kgH_2/1000 km)
4. Fuel cell efficiency (%)
5. Storage costs (€/kg)
6. Carbon price (When compared with natural gas) (€/CO_2ton)

Ignored factors:

1. Capex of electrolyser and fuel cell
2. Maintenance cost of electrolyser and fuel cell

The transportation loss was assumed to be 2 % which Professor van Wijk (2019) used in his study. Transportation losses are affected by the pipe's diameter, distance, and several other factors, but a fixed estimate of transportation losses is sufficient to describe these scenarios' situation. A lower heating value of 33.33 kWh per kilogram of hydrogen was used as energy content in these calculations. Hydrogen storage costs were estimated to be around 3 % in each scenario, as presented in previous Section 4.3 based on the master's thesis study by Laban (2020). The electrolyser and fuel cell's operating cost (Opex) are estimated to be around 5 €/MWh, which is equal to 0.17 €/kgH_2 when LHV-based energy content of hydrogen, 33 kWh/kg is taken into account. Due to the similar operational principle of electrolyser and fuel cell, and the lack of actual large-scale projects, this same Opex is assumed to be the same for both technologies and each scenario.

The effect of changes in parameters on the final price was observed. The final price means the price of electricity generated at the end of the shifting process via fuel cells, and it could also be called an end or final product of the shifting process. In order for green hydrogen to become a suitable long-term energy storage option, this price should be lower than the price of electricity in consumption peaks. The price of the end product (electricity) of the shifting process does not compete with the price of a base generation of renewable electricity. Still, lower costs of available renewable power support the competitiveness of the shifting process.

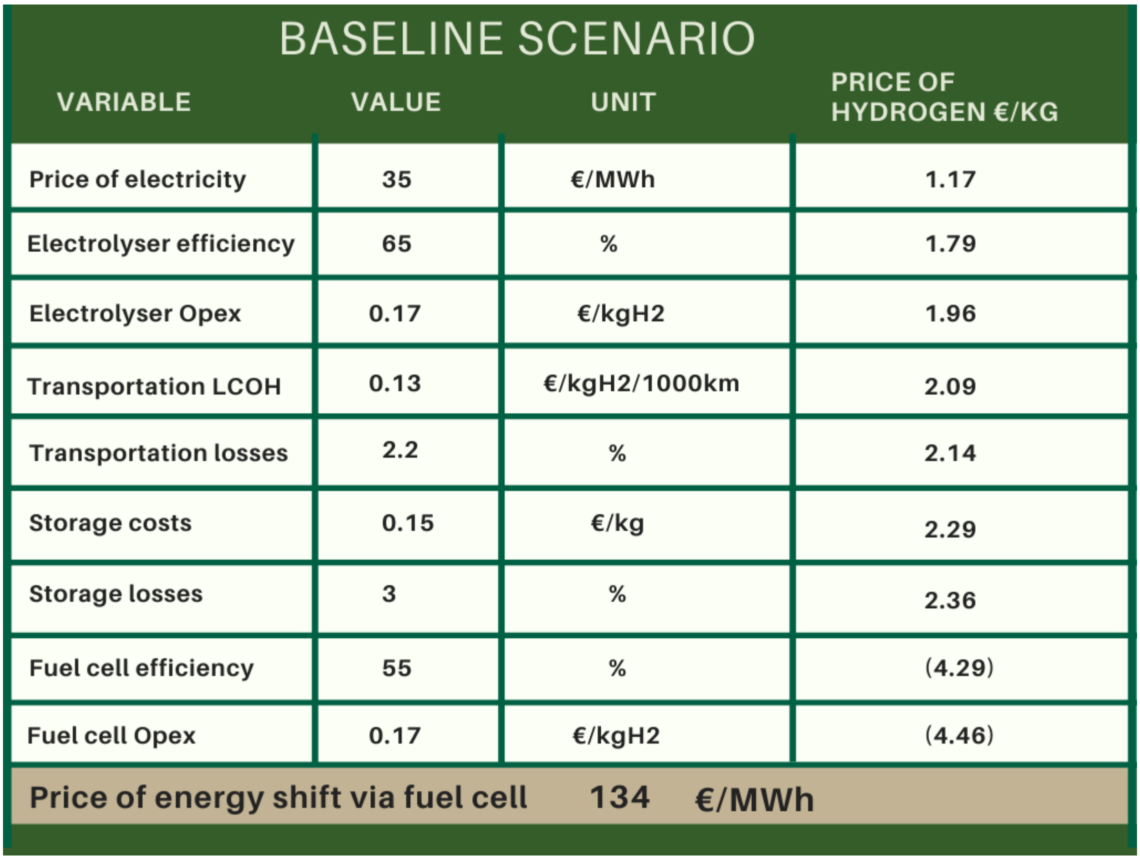
The baseline scenario was firstly created, and its values were determined based on the several studies already presented earlier in this thesis. Table 4 introduces the values for baseline scenarios and the price of electricity produced via fuel cell technology. The price of electricity was chosen based on earlier studies. For instance, Christensen (2020) uses 30 – 50 €/MWh price for directly connected onshore wind power. In these scenarios, directly connected onshore wind was also used, and that is why 35 €/MWh was chosen for the baseline scenario. Additionally, Statista (2020) showed that the average grid price of wind power in the EU was around 30-40 €/MWh in countries where wind power is widely utilised. As presented in Section 3.2.2, IRENA has estimated the LHV efficiency of electrolysers around 68 % by 2030. Based on that analysis and previous development, 65 % efficiency was used in the baseline scenario.

The levelized cost of hydrogen in transportation is based directly on the previously presented hydrogen backbone strategy where LCOH in transportation was 0.13 €/kg/ 1000 km in the medium scenario. Transportation costs estimates are divided into three categories in the backbone strategy. A medium-cost forecast in the baseline scenario made sense as it gets a place between ideal and conservative conditions. To simplify the calculations, it was assumed that 1000 km transportation of hydrogen to fuel cell power plant is required on average.

BNEFs estimated costs about storing hydrogen in salt caverns were used for these calculations as well. Based on the analysis, the price of storage varies from 0.1 €/kg to 0.21 €/kg (BloombergNEF 2020). Therefore, the price of 0.15 €/kg was used in the baseline scenario. LHV-based fuel cell efficiency of 55 % was used in this scenario (U.S.

Department of Energy 2015). The baseline scenario is presented in following Table 4. The price of hydrogen column is indicating the hydrogen price per kilogram in each of the points. The price is lower and increases as more stages of the process are taken into account.

Table 4. Baseline scenario for the process of hydrogen production and utilisation in the fuel cell technology to produce electricity.



BASELINE SCENARIO

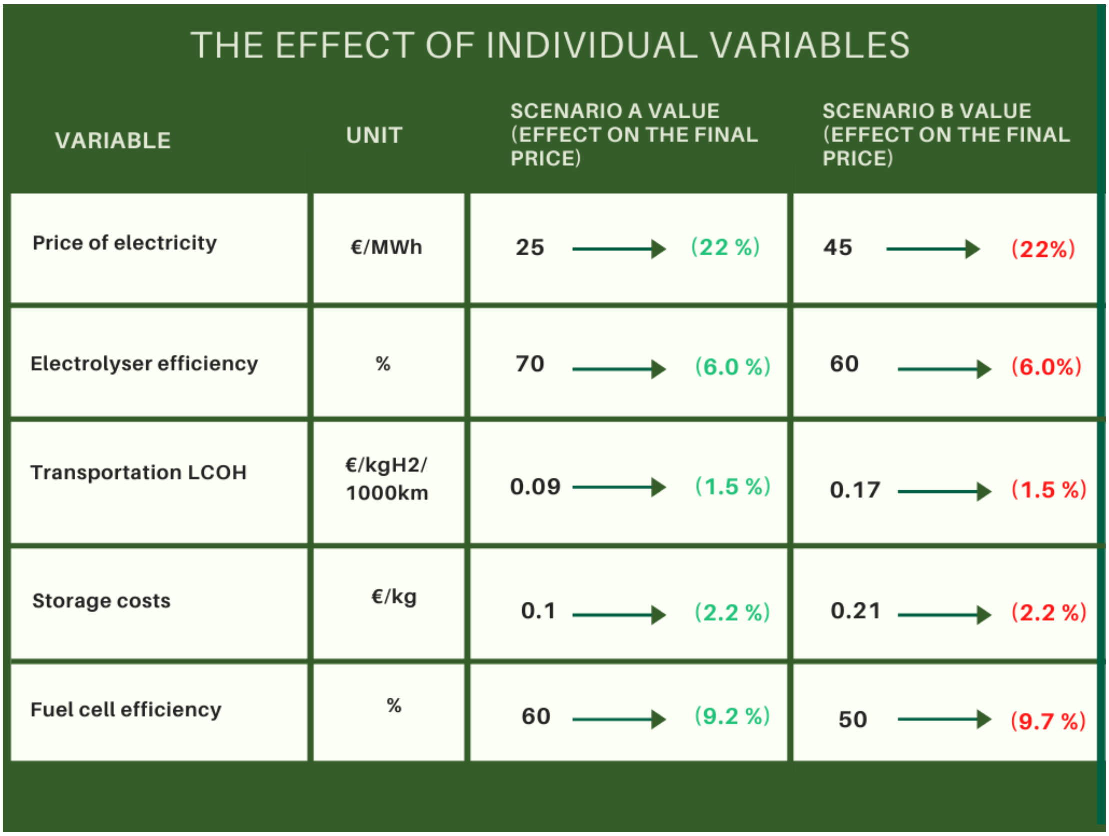
VARIABLE	VALUE	UNIT	PRICE OF HYDROGEN €/KG
Price of electricity	35	€/MWh	1.17
Electrolyser efficiency	65	%	1.79
Electrolyser Opex	0.17	€/kgH2	1.96
Transportation LCOH	0.13	€/kgH2/1000km	2.09
Transportation losses	2.2	%	2.14
Storage costs	0.15	€/kg	2.29
Storage losses	3	%	2.36
Fuel cell efficiency	55	%	(4.29)
Fuel cell Opex	0.17	€/kgH2	(4.46)
Price of energy shift via fuel cell	134	€/MWh	

The baseline scenario shows that the final price is formed mainly by the cost of renewable electricity, fuel cell technology efficiency, and electrolyser efficiency. If the cost of renewable electricity cannot be influenced, the most crucial development objects are the electrolyser and fuel cell technologies' efficiencies. The price of 134 €/MWh is too high to compete with Europe’s current electricity generation. The following section will study how the change in each variable affects on the final price.

5.2 Variable analysis

The analysis was performed by changing the variables one by one. This kind of approach enables a more efficient way to identify each variable's effect on the final price. The impact of the variables is first presented in Table 5 and then explained verbally. Table 5 lists the variables according to Scenarios A and B. The parenthesis value represents how many percentage points change the individual variable change would cause if other variables were kept on the same level as in the baseline scenario. The green values mean that effect will be positive so that the final price will be lower than in the baseline, and red values indicate that the impact is negative and the final price increases. The table indicates that the cost of renewable electricity and the efficiency of technologies have the most significant impact on the final price in these scenarios.

Table 5. The changing parameters in the scenarios and their individual effect on the final price compared to the baseline scenario.



THE EFFECT OF INDIVIDUAL VARIABLES

VARIABLE	UNIT	SCENARIO A VALUE (EFFECT ON THE FINAL PRICE)	SCENARIO B VALUE (EFFECT ON THE FINAL PRICE)
Price of electricity	€/MWh	25 → (22 %)	45 → (22%)
Electrolyser efficiency	%	70 → (6.0 %)	60 → (6.0%)
Transportation LCOH	€/kgH2/ 1000km	0.09 → (1.5 %)	0.17 → (1.5 %)
Storage costs	€/kg	0.1 → (2.2 %)	0.21 → (2.2 %)
Fuel cell efficiency	%	60 → (9.2 %)	50 → (9.7 %)

5.2.1 The effect of renewable electricity price

In these scenarios, wind power's price represents a significant role in the price of the end product. The purpose of calculations was to show the potential of green hydrogen if the development of costs and efficiencies continue positively. Therefore, the cost of renewable electricity drops from 35 €/MWh to 25 €/MWh by 2030 in scenario A. Although the price is low, this kind of development is already visible in Europe. The price of electricity in scenario B is chosen according to the conservative evaluation that the price will rise to 45 €/MWh.

In case that all other variables are kept constant as in the baseline scenario, and the price of renewable electricity is 25 €/MWh, the final price of hydrogen decreases from 2.36 €/kg to 1.82 €/kg. Also, the cost of electricity via fuel cell would fall from 134 €/MWh to 104 €/MWh, which corresponds to a drop of over 20 % in electricity price.

In turn, if the price of renewable energy increases in line with scenario B to 45 €/MWh, the final price of hydrogen would be 2.9 €/kg and the cost of electricity produced by the fuel cell 163 €/MWh which is more than 20 % higher compared to the baseline. Based on the results, it can be concluded that the cost of green hydrogen is strongly dependent on the price of renewable energy available for electrolysis. However, it needs to be noted that the price range of renewable energy is wide in these scenarios.

5.2.2 Efficiency of electrolyser

As a continuation of the price of electricity, the next consideration is a crucial technological factor in green hydrogen production, and it is the efficiency development of electrolysers. Several pieces of research and commercial articles have tried to assess the development, but a common vision has not been found. Also, there are multiple views on what kind of electrolyser efficiencies are currently achieved on average. IRENA’s report at innovation week (2020) was used as a source in this thesis to evaluate electrolysers efficiency, according to which current conversion efficiency is about

65 % and could be increased to as high as 75 % by 2050. Therefore 70 % efficiency has been used in scenario A, 60 % in scenario B, and 65 % efficiency in the baseline scenario.

While other variables were kept at the same level as in the baseline scenario, and only electrolyser efficiency was increased by 5 % points to 70 %, an over six percentage points decrease from in the price of electricity from 134 €/MWh to 126 €/MWh was achieved. If efficiency decreased to 60 % and no changes in the other factors, the final product price would be about six percentage points higher than in the baseline scenario rising to 142 €/MWh. In summary, along with the cost of renewable electricity, improvements in electrolyser technology are significant for the feasibility of green hydrogen in the electricity generation sector.

5.2.3 Transportation Levelized Cost of Hydrogen

A comprehensive network for hydrogen transportation is required when hydrogen cannot be utilised immediately next to the production site. In Chapter 4, it was stated that pipeline solution is the most efficient way to transfer hydrogen in large quantities. Hydrogen backbone strategy was used as a basis of the present calculations, and in scenario A, LCOH transportation was 0.09 €/kg. This 30 % decrease in transportation costs would decrease the final product's price by less than 2 %. In scenario B, the LCOH transportation was increased by 30 % from baseline to 0.17 €/kg, and it would only increase the final price by less than 2 %. These figures were estimated based on the case where 75 percent of the transportation line is retrofitted, and 25 % is new infrastructure. An additional uncertainty aspect is that these values represent the cost of transported hydrogen per 1000 km.

5.2.4 Cost of storage

Renewable energy production is highly dependent on weather conditions, making it impossible to provide a constant amount of energy to electrolysers. Without the storage capacity of hydrogen in electricity generation, the situation where electricity can be generated when additional power is needed cannot be achieved. BloombergNEF (2020) has estimated that hydrogen's levelized cost of storage in salt caverns varies between 0.1 €/kg to 0.21 €/kg. If other variables are kept constant, and storage costs are dropped from 0.15 €/kg (baseline) to 0.1 €/kg, the final price of converted electricity would fall from 134 €/MWh to 131 €/MWh. In turn, if the cost of storage would increase to a value of 0.2 €/kg, the price of electricity would rise by 3 €/MWh to 137 €/MWh.

Although transportation cost represents a small share of the total costs, improvements in hydrogen storage technology can significantly reduce the final price. There are still several uncertainties in hydrogen storage technology, and therefore the range of price estimates is wide. In addition, these calculations did not take into account capital costs, which are estimated to be substantially high in hydrogen storage in 2030.

5.2.5 Efficiency of fuel cells

The fluctuation range of efficiency has been selected based on the fact sheet released by the U.S. Department of Energy (2015). The impacts of fuel cell efficiency developments on the final electricity price of the shifting process are presented with the following bullet points:

1. If the efficiency of fuel cells were improved by 5 % to 60 %, the final price of electricity would decrease by 9 % from 134 €/MWh to 123 €/MWh.

2. If the fuel cells' efficiency were decreased by 5 % to 50 %, the final price of electricity would increase by 10 % from 134 €/MWh to 147 €/MWh.

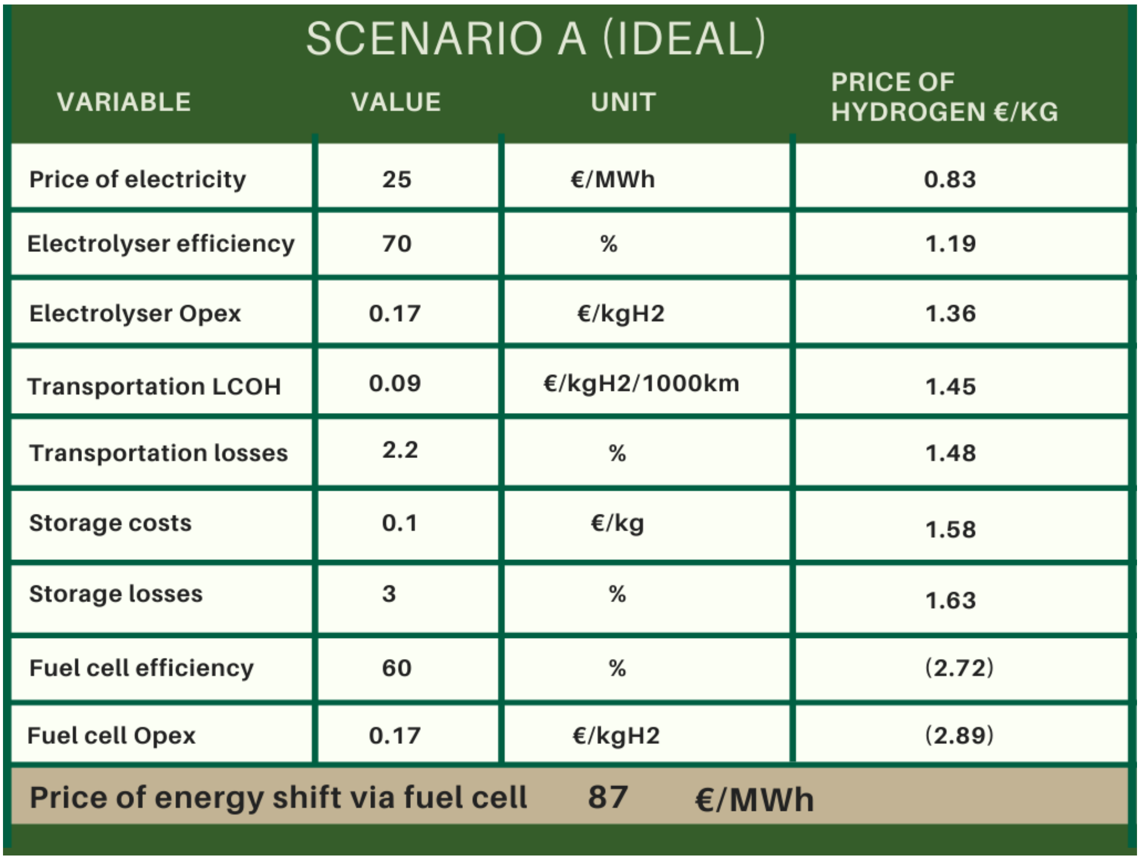
5.3 Scenario comparison and blend with natural gas

Two different scenarios were reviewed in this section, of which B is more conservative than the baseline, and A is more ambitious. The end product prices based on the scenarios were compared with each other and with the price of electricity produced by a blend of natural gas and hydrogen. It was also considered how high the carbon price should be in different scenarios for green hydrogen to be a profitable electricity generation option.

5.3.1 Scenario A vs B

Finally, a situation where all variables are changed according to the scenario A and B is presented. Under the ideal conditions, all of the previously given changing parameters are set based on scenario A. It would lead to an "ideal" situation. According to calculation, the Power-to-Gas-to-Power conversion process's output would be the electricity production via fuel cell at the price of 87 €/MWh. These results are visible in Table 6.

Table 6. Power to Gas to Power shifting process and its costs under ideal conditions. (Scenario A)

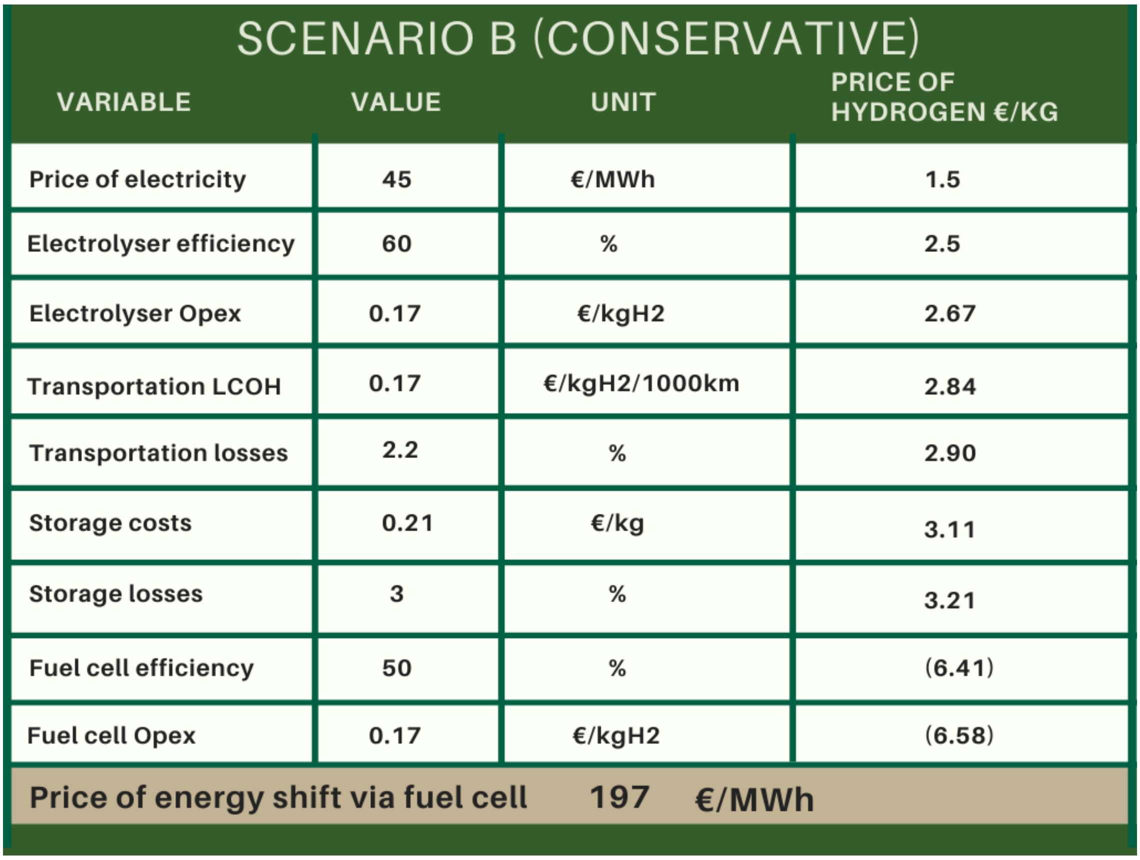


SCENARIO A (IDEAL)

VARIABLE	VALUE	UNIT	PRICE OF HYDROGEN €/KG
Price of electricity	25	€/MWh	0.83
Electrolyser efficiency	70	%	1.19
Electrolyser Opex	0.17	€/kgH2	1.36
Transportation LCOH	0.09	€/kgH2/1000km	1.45
Transportation losses	2.2	%	1.48
Storage costs	0.1	€/kg	1.58
Storage losses	3	%	1.63
Fuel cell efficiency	60	%	(2.72)
Fuel cell Opex	0.17	€/kgH2	(2.89)
Price of energy shift via fuel cell	**87**	**€/MWh**	

If all variables do not evolve in the best possible way but instead remain on the current level, the cost of the conversion process would be significantly more expensive than in Scenario A. The results based on that assumption are shown in Table 7. It is noticeable that Scenario B's parameters deteriorate hydrogen's competitiveness and lead to a 2.3 times higher final price of electricity than in A. The final electricity price of the shifting process would be 197 €/MWh in this case.

Table 7. Power to Gas to Power shifting process and its costs in conservative scenario. (Scenario B).



SCENARIO B (CONSERVATIVE)

VARIABLE	VALUE	UNIT	PRICE OF HYDROGEN €/KG
Price of electricity	45	€/MWh	1.5
Electrolyser efficiency	60	%	2.5
Electrolyser Opex	0.17	€/kgH2	2.67
Transportation LCOH	0.17	€/kgH2/1000km	2.84
Transportation losses	2.2	%	2.90
Storage costs	0.21	€/kg	3.11
Storage losses	3	%	3.21
Fuel cell efficiency	50	%	(6.41)
Fuel cell Opex	0.17	€/kgH2	(6.58)
Price of energy shift via fuel cell	197	€/MWh	

5.3.2 Hydrogen blends and natural gas in electricity generation

A cost comparison with other energy sources is needed to identify the magnitude and competitiveness of the results. In cost comparison, the role of green hydrogen in electricity generation needs to be taken into account. The increasing number of renewables in the power system reduces emissions and increases the need for control power and energy storage.

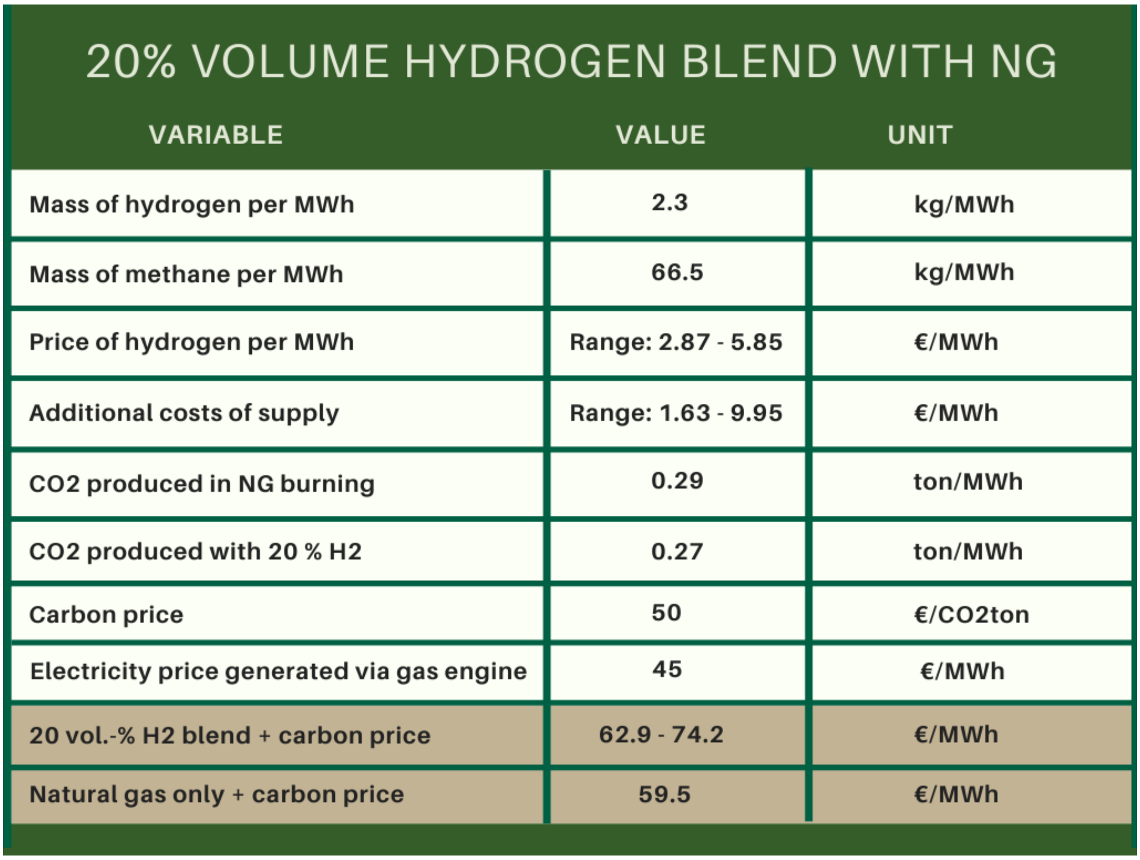
One of hydrogen's key values in the energy sector is operating as long-term energy storage, as mentioned in previous chapters. Due to different purposes and reasons in the electricity sector, comparison with renewable electricity prices does not make sense. Instead, this section compares the costs of natural gas and green hydrogen blends with the cost of purely natural gas used in internal combustion engines. The benefit of blending is that green hydrogen can be fed into the electricity market, which will reduce carbon dioxide emissions and thus decrease costs caused by the emissions penalty. As a disadvantage in a blending option, additional charges are caused due to green hydrogen production, and supply costs increase. The section aimed to assess whether the positive effects are more remarkable than negative ones and whether blending would be a cost-effective option. Most of the values used in the calculations have been selected based on the estimated future developments presented in the previous Chapters.

This analysis assumed that 20 vol.-% of hydrogen is blended with natural gas and fed to the existing pipeline. As presented in Section 4.1, 20 % mixing has been found to achieve the best engine performance and low emissions at the same time. When the energy and mass content of hydrogen per MWh is calculated, it is observed that the proportion of hydrogen is minor; only 7.6 % of the energy content is hydrogen. Since the engine naturally produces about 290 kg/MWh of carbon dioxide emissions when fuel injection is 150 degrees before the top dead centre (Çeper 2020), emissions can only be reduced approximately by the amount of energy content of hydrogen. In this 20 % blend, carbon dioxide production would be roughly 270 kg/MWh.

The modified pipeline's cost has been selected based on the research (Melaina, Antonia & Penev 2013) that estimates the extraction cost of hydrogen to be 4.2 €/kgH_2 on average and in this configuration would correspond to the cost of 10 €/MWh. However, the same report states that additional supply chain costs could be as low as 0.8 €/kgH_2 on average if hydrogen can be extracted at a pressure-reduction site and high recompressing costs of natural gas can be avoided. In this case, it would be equivalent to the cost of 1.6 €/MWh. Worth noting is that the research used as a source is already several years old and does not necessarily fully reflect the current costs. Also, in the coming years, prices are more likely to continue to reduce than the increase from the current levels. However, these values are indicative and accurate enough for the present calculations.

The cost of natural gas has been selected according to imported natural gas data in Europe. Ycharts (2020) indicates that the average price of imported natural gas in Europe from the beginning of 2019 to November 2020 has been approximately 3.9 €/MMBTU. Converting that average gives a result of 14 €/MWh. A lot of volatility has been observed in the prices over years and recent months. During the coronavirus outbreak, the cost of imported natural gas in the EU fell in summer 2020 to as low as 5.4 €/MWh, while in September 2018, the price was 33 €/MWh. Due to the exceptionally low natural gas prices in 2020, previous year was also included in the average review. It was assumed that these values represent the price based on HHV, so the LHV basis price can be calculated by multiplying 13.5 by a factor of 1.11, which is approximately 15 €/MWh. After considering possible running cost and total efficiency of about 45 % of the gas-fuelled engine-based power plant, it is estimated that electricity is typically generated at 45 €/MWh without a carbon price. Following Table 8 shows the price of electricity generated by a gas engine when the natural gas is mixed with 20 vol. -% of hydrogen and carbon price is 50 €/MWh.

Table 8. Cost review of 20 vol. -% hydrogen blend with natural gas.



20% VOLUME HYDROGEN BLEND WITH NG

VARIABLE	VALUE	UNIT
Mass of hydrogen per MWh	2.3	kg/MWh
Mass of methane per MWh	66.5	kg/MWh
Price of hydrogen per MWh	Range: 2.87 - 5.85	€/MWh
Additional costs of supply	Range: 1.63 - 9.95	€/MWh
CO2 produced in NG burning	0.29	ton/MWh
CO2 produced with 20 % H2	0.27	ton/MWh
Carbon price	50	€/CO2ton
Electricity price generated via gas engine	45	€/MWh
20 vol.-% H2 blend + carbon price	62.9 - 74.2	€/MWh
Natural gas only + carbon price	59.5	€/MWh

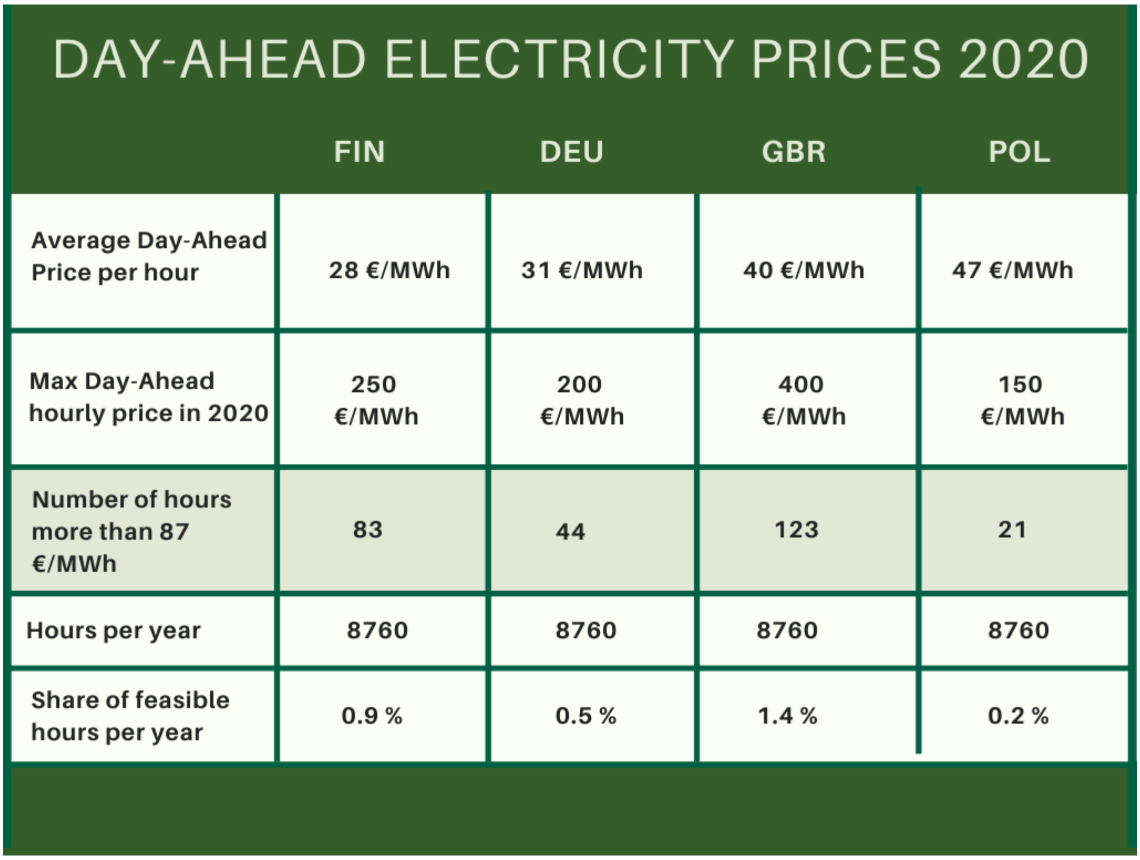
The first observation from Table 8 is that CO_2 emission reduction is relatively small with a 20 % volume-based blend. Increasing the emission price has minimal effect on the cost-competitiveness of hydrogen blend when comparing that option with traditional natural gas-fuelled power plants. If green hydrogen could be blended in the cheapest possible way with natural gas as presented in Table 8, the emission price of 225 €/ CO_2ton would be required to make blending feasible in the light of costs. However, no direct conclusions that the hydrogen blend is not a reasonable option for decarbonisation cannot be done based on these results. Further studies and practical tests on the use of hydrogen blend need to be done.

Based on the calculations presented above, green hydrogen will have a challenging path to become cost-competitive with natural gas in electricity generation. Nevertheless, it is advisable to remember that one of the primary purposes of green hydrogen is to be long-term storage for surplus energy of renewables. The value of that property was not taken into account in these calculations. Additionally, methane is tens of times more potent greenhouse gas than carbon dioxide (Hamburg 2020). One of the factors that distress natural gas use is methane leaks at production sites, pipelines, and final consumption sites. Due to the small size of hydrogen molecules, the leaks are common and may cause the risk of fire or explosion, especially in an enclosed environment. However, hydrogen leakage itself is not hazardous and does not release greenhouse gas into the atmosphere like methane. Using hydrogen in a blend, methane leaks can be reduced, but that benefit has not been considered in these calculations.

5.4 Peak prices in the European electricity market

Due to different circumstances, the price of electricity varies across the EU as a function of time, flexibility, and location. Because of fluctuating demand and lack of electricity storage, price of electricity does not remain constant throughout the day. Several different electricity markets operating in the EU determine the price of electricity, sometimes even in 15 minutes time frames. In terms of keeping electricity supply and demand in equilibrium and maintaining frequency on the level of 50 Hz within the EU, balancing markets is in place. (Reif & Schittekatte 2020). In this section, the EU's 2020 day-ahead prices were examined on an hourly basis. Four countries, Finland, Germany Poland, and the United Kingdom, were selected for country-specific electricity price comparison, as visible in Table 9. Countries were chosen in such a way that their average day-ahead prices in 2020 were not identical. Table 9 shows the maximum day-ahead prices at an hourly level in 2020 and the average prices. The most interesting part of Table 9 can be found from the line with a grey background, where the number of hours when the price of electricity has been over 87 €/MWh are presented. 87 €/MWh represents the price at which green hydrogen could be used to produce electricity via fuel cell under ideal conditions.

Table 9. Country-specific comparison of day-ahead electricity prices in 2020 and feasibility of green hydrogen-based plant.



DAY-AHEAD ELECTRICITY PRICES 2020

	FIN	DEU	GBR	POL
Average Day-Ahead Price per hour	28 €/MWh	31 €/MWh	40 €/MWh	47 €/MWh
Max Day-Ahead hourly price in 2020	250 €/MWh	200 €/MWh	400 €/MWh	150 €/MWh
Number of hours more than 87 €/MWh	83	44	123	21
Hours per year	8760	8760	8760	8760
Share of feasible hours per year	0.9 %	0.5 %	1.4 %	0.2 %

The results in Table 9 were calculated based on the data from European Cooperation Organization Entso-E (2021). The average Day-Ahead price of electricity in Finland was the lowest within the comparison countries and up to 60 % lower than Poland's price. Again, it is worth noting that all electricity markets and actual prices are not included in this comparison. Factors such as the coronavirus pandemic that contributed to the drop in the electricity demand in 2020 certainly create uncertainty in country-specific results comparability.

Although average hourly prices are fairly moderate, a closer look reveals significant variations in prices within a year, and high peak prices are emerging. Based on these findings, a review was conducted to determine the number of hours per country, with an average peak price of more than 87 €/MWh. Simplified, this means that power plants powered by hydrogen are feasible to operate when the plant can generate electricity below peak prices. The results show that, for instance, in Finland, it would have been profitable to run a hydrogen-based power plant for approximately 83 hours if that plant could produce electricity at 87 €/MWh. The amount is not a high percentage of all hours per year but based on the figures for green hydrogen-based power plants, the potential to become a competitive source of electricity exists. In Section 5.3.1, the electricity price under ideal conditions was calculated based on the assumption that the plant is operating continuously, which means a lower load will lead to higher prices. In following Figure 13, it was simulated how many more feasible hours would be added per year in these four different countries if the price of electricity generated via a hydrogen-powered power plant could be reduced under 87 €/MWh.

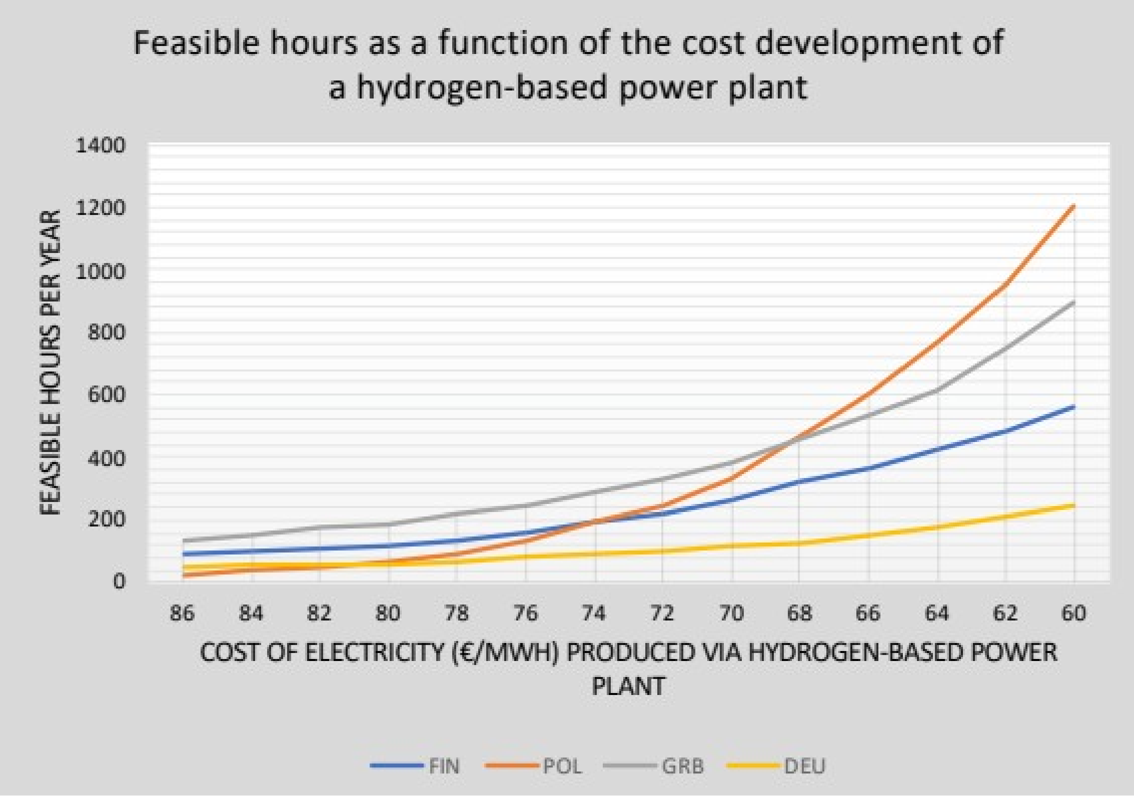


Figure 13. An increase in the number of feasible hours as a result of cost reduction.

Differences between the countries increase rapidly as a function of price and for example, there would be multiple times more feasible hours in Poland than Germany at the price of 60 €/MWh. The number of feasible hours remains low in Germany even when going closer to the average, hour-basis, day-ahead price.

5.5 Discussion

This section evaluates the significance of the study, research findings and the accuracy of the results. The purpose of the discussion is to define how the findings are related to each other and their limitations. To assess whether hydrogen is a feasible option for electricity generation or not, the market potential was examined via several commercial and scientific sources that mainly deal with demand, technical aspects, and costs analysis of the hydrogen economy.

The review of the EU's ambitious hydrogen strategy at the beginning of the thesis revealed a real political will towards the hydrogen economy. However, ambitious strategies and targets do not decarbonise the sectors themselves, so actual projects are needed, indicating a true state of mind. The success and cost-effectiveness of the green hydrogen economy are currently highly dependent on public subsidies. Achieving competitiveness in electricity generation will require significant financial support for several years. The more countries and companies are involved in developing the hydrogen economy at the same time, the faster cost reductions can be expected.

The demand for green hydrogen within all different sectors and especially in electricity generation, was examined in the second section. According to the findings, industrial and transport sectors are gaining the strongest green hydrogen utilisation rate at the beginning. Industrial processes seem promising due to high volume demand and easier integration into existing systems than in many other sectors. However, the accurate assessment of hydrogen demand in different sectors is challenging and may include several uncertainties. It is also visible in commercial sources used in this study as a fluctuating estimate.

Continuous development and rapidly changing circumstances in the hydrogen economy can be considered as limitations of the assessments presented in this thesis. Market potential analyses and calculations in this thesis are highly related to the time of writing at the end of 2020 and the beginning of 2021. A comprehensive comparison of electricity generation technologies via hydrogen in this study was limited due to the awareness that, for example, 100 % hydrogen-powered engines have not yet developed to commercial operation when the actual advantages would only become clear. Large-scale hydrogen-based power plant projects will show the feasibility of each solution.

Transportation and storage of hydrogen is a fascinating topic of research, and their evolution will strongly contribute to the success of the green hydrogen economy. This thesis focused on studying the most recently released hydrogen transportation strategies and analysis of storage capabilities. Most costs and efficiency estimates are based on the available analysis by organizations and companies and not on actual projects, which causes uncertainties in the reality of values. A relatively minor amount of hydrogen infrastructure has been built, and hydrogen storage in salt caverns is still largely under development. Despite these aspects, the transportation and storage section is highly relevant for electricity generation and is also an essential part of this thesis and necessary for the calculations in Chapter 5.

The most significant outcome of the thesis can be considered the results in Chapter 5, which supports the theoretical part through practical calculations. The section utilises the estimates of technological and financial development of the green hydrogen economy presented in previous sections. Calculations are not based on actual projects and it definitely needs to be taken into account when assessing the integrity of the results. There is no uniform target year used in the background of the scenarios, but most of the calculations' values were expected to be a reality around 2030 – 2040. Also, the calculations were simplified to make them feasible to implement within the framework of this thesis. For example, Capital expenditures of electrolyser and fuel cell were ignored in these calculations. Capex might be significant, but in this case, were considered as a market bidding investment for plants and therefore is not included in the price of green hydrogen.

The comparison of green hydrogen competitiveness with natural gas-fuelled power plants did not consider the possible widespread use of CCS technology, which will reduce high carbon prices. Despite the possibility of faults and inaccuracies in calculations, the results indicate the range of values required for green hydrogen to become a cost-competitive peaking option in electricity generation.

Comparison of the four EU countries' day-ahead electricity prices revealed the number of hours with high peak prices. Only the free data source maintained by Entso-E on hourly basis day-ahead prices was used in reviews. It was possible to estimate the feasibility of green hydrogen in electricity generation via simplified calculations. However, more accurate results were not achieved due to ignoring other actual electricity market prices like the balancing market. Day-ahead market price analysis was still considered to expand the view of green hydrogen feasibility in electricity generation.

6 Conclusions and recommendations

This thesis focused on reviewing the feasibility of green hydrogen in electricity generation. Analysing the recently published hydrogen objectives and strategies by the EU, technological and economic challenges, and creating own scenario calculations were the main part of the thesis. The work's main conclusions were collected to the following lists, and further research recommendations were made based on the results. By comparing hydrogen strategies and technologies, the following observations were made about the hydrogen economy and its development around Europe:

1. The European Union's extremely ambitious strategy to multiply the production and use of green and other low carbon hydrogens by 2030 will steer the transition.
2. Several Member States have published their strategies, according to which Germany is making the largest investments in terms of volume and achieving the most robust hydrogen economy in Europe.
3. In light of current information, internal combustion engines, gas turbines, and fuel cells are the most promising electricity generation options via hydrogen. Future development of technologies will show which technologies and companies will gain the strongest market share.

Recommendations: The EU's Member States' level of commitment to their hydrogen strategies could be an exciting area for further studies to assess whether the hydrogen economy is developing in the right direction on the desired schedule.

Although the European Union is investing heavily in the decarbonisation of hydrogen economy and potential technologies, the large-scale use of pure hydrogen in electricity generation still includes several challenges. The following list summarises the challenges that electricity generation may face in the coming years in hydrogen use:

1. Sectors like industrial, where the deployment of green hydrogen is easier and more efficient, will gain the strongest demand in the beginning. Therefore, availability for the needs of electricity generation is lower.
2. To enable power plants to operate on hydrogen and be a competitive peaker option, hydrogen distribution network connection and storage potential such as salt caverns are required.

Recommendations: Examine the commitment of industrial actors to decarbonise their processes via green hydrogen and compare this amount with the EU's targets.

Based on the findings of the thesis, the following conclusions can be made about the transportation and storage of hydrogen, which are essential parts from the electricity generation perspective:

1. In early-stage deployment, due to lower costs, mainly existing natural gas pipelines with low load factors will be converted to be suitable for hydrogen use.
2. Within the EU, the greatest potential to store hydrogen is in salt caverns. The amount of storage capacity is not seen as a problem, but technical and financial issues still need to be overcome before large-scale introduction.
3. It seems that infrastructure will be built when the production of green hydrogen starts to increase, and investments in power plants will begin after the proper infrastructure is ready. It is one reason why electricity generation is not the first sector with a high utilisation level of green hydrogen.

Recommendations: A study of actual transportation and storage projects could be conducted. That information advantage could help electricity generation actors be well prepared for growth in the green hydrogen market.

The different scenario calculations for the feasibility of green hydrogen in electricity generation were presented in this thesis. Conclusions drawn based on the calculations:

1. Green hydrogen-fuelled power plants could be competitive under ideal conditions, but the costs and technologies are not yet at that point of development.
2. In the early phase, blending hydrogen with natural gas may be a reasonable option due to existing technologies and infrastructures which can handle the blend. However, minimal emission reductions indicate that this is not a feasible solution in the long run and will be the most probable option for the transition phase only.
3. The instability of electricity networks grows when the share of renewable energy sources increases. A hydrogen-based power plant may be a feasible option for seasonal storage if the most ideal conditions used in the calculations could be achieved.

Recommendations: Further examinations of calculations presented in this study could provide more accurate data about the feasibility of green hydrogen in electricity generation. Reviewing the number of feasible hours per country, taking into account all actual electricity market prices, could provide more useful information.

7 Summary

As the current energy transition continues, a dramatic drop in the use of fossil fuels and exponential growth in the share of renewables will be faced. In addition to reducing emissions, the development will also cause imbalances in the electricity system stability. The need for control power is real, and in line with short-term energy storage, long-term storage capacity is needed, for which a pure gas such as green hydrogen could be a potential alternative. From these starting points, the need and importance for this study aroused.

The thesis's purpose was to conduct a study on the green hydrogen feasibility in electricity generation in Europe. The analysis of the thesis was based on scientific and commercial articles about market potential and technologies. The literature review indicated positive signs of future development, and a very high level of ambition was evident in recently released hydrogen strategies. The proper infrastructure and the development of electricity generation technologies via hydrogen would play a key role in the success of green hydrogen in the electricity generation sector. Several technological challenges in electricity generation options are related to hydrogen's characteristic behaviour, such as lightness and sensitive self-ignition. According to the hydrogen strategies, existing natural gas infrastructure will be converted and utilised for the use of hydrogen at the initial phase.

Based on the calculations, green hydrogen may be a feasible option for the electricity shifting process and operate as long-term storage under ideal conditions, where hydrogen can be produced, transported, stored, and converted back to electricity at an affordable price. Nevertheless, to achieve these targets, significant investments in the research and development of hydrogen-related technologies are required. It seems that blending hydrogen with natural gas is the viable option, only in the transition phase. Only minor emission reductions can be achieved by this solution, however. When the number of renewables increases in the system, clean, load-following power plants are increasingly needed. There is potential for green hydrogen here, as well.

Green hydrogen has a great potential to become a significant factor and missing piece in electricity generation, but the required cost-effectiveness level has not yet been achieved.

References

Adler, Kevin (2020). Europe emerges as leader in hydrogen economy. [Online]. [25.9.2020] Available: https://ihsmarkit.com/research-analysis/europe-emerges-as-leader-in-hydrogen-economy.html

BloombergNEF (2020). Hydrogen Economy Outlook. [Online]. [25.1.2021] Available: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Bruninx, K., Ovaere, M. & Delarue, E. (2020). The long-term impact of the market stability reserve on the EU emission trading system. [Online]. [5.10.2020] Available: https://www.sciencedirect.com/science/article/pii/S0140988320300852?casa_token=I04evZFmR6gAAAAA:WCOIzFo6yi5KSkNBHD6usCM3dvk0ImpI74YgXk6idaX2VH3Byskf8RQyUx6HxRU2n7lTAw2pKUWi

Buseman, M., Peters, D., van der Leun, K., & Wang, A. (2020). European Hydrogen Backbone. [Online]. [22.10.2020] Available: https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/

Caglayan, D. G., Heinrichs, H. U., Kukla, P. A., Linssen, J., Robinius, M., Stolten, D. & Weber, N. (2020). Technical potential of salt caverns for hydrogen storage in Europe. [Online]. [27.10.2020] Available: https://www.sciencedirect.com/science/article/abs/pii/S0360319917306122?casa_token=Buo0yVJ-7UMAAAAA:aZ_E3oJHbrMlEzPesSufivh7Wha9ICJ3cun_vDkWlTVUa1cO1NEw48tcTBlXeHl7ukpKXQsVsS4

Cappelletti, A. & Martelli, F. (2017). Investigation of a pure hydrogen fueled gas turbine burner. [Online]. [11.1.2021] Available: https://www.sciencedirect.com/science/article/abs/pii/S0360319917306122?casa_token=Buo0yVJ-7UMAAAAA:aZ_E3oJHbrMlEzPesSufivh7Wha9ICJ3cun_vDkWlTVUa1cO1NEw48tcTBlXeHl7ukpKXQsVsS4

Çeper, B. A. (2012). Use of Hydrogen-Methane Blends in Internal Combustion Engines. [Online]. [25.9.2020] Available: https://www.intechopen.com/books/hydrogen-energy-challenges-and-perspectives/use-of-hydrogen-methane-blends-in-internal-combustion-engines

CerifHY (2019). An Emerging Green and Low Carbon Hydrogen Market in Europe. [Online]. [7.1.2021] Available: https://www.certifhy.eu/9-uncategorised/174-an-emerging-green-and-low-carbon-hydrogen-market-in-europe.html

Christensen, A. (2020). Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe. [Online]. [27.10.2020] Available: https://theicct.org/sites/default/files/publications/final_icct2020_assessment_of%20_hydrogen_production_costs%20v2.pdf

COAG Energy Council (2019). Australia’s national hydrogen strategy. [Online]. [2.10.2020] Available: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf

Deutsch, A. & Graf, A. (2019). EU-wide innovation support is key to the success of electrolysis manufacturing in Europe. [Online]. [30.12.2020] Available: https://www.agora-energiewende.de/en/blog/eu-wide-innovation-support-is-key-to-the-success-of-electrolysis-manufacturing-in-europe/

Dodgshun, Joe (2020). Hydrogen: Clearing up the colours. [Online]. [20.12.2020] Available: https://www.enapter.com/hydrogen-clearing-up-the-colours

Edie (2020). EU carbon price to reach €32 by 2030, short of required price for UK's net-zero target. [Online]. [20.11.2020] Available: https://www.edie.net/news/6/EU-carbon-price-set-to-rise-to-EUR32-by-2030--but-experts-say-EUR81-necessary-to-achieve-net-zero-in-the-UK/

Elaoud, S., Hafsi, Z. & Mishra, M. (2018). [Online]. [10.10.2020] Available: https://www.sciencedirect.com/science/article/pii/S2452321618302683

EPA (2018). Greenhouse gas emissions from a Typical Passenger Car. [Online]. [5.10.2020] Available: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

European Commission (2020a). The EU steel industry. [Online]. [16.10.2020] Available: https://ec.europa.eu/growth/sectors/raw-materials/industries/metals/steel_en

European Commission (2020b). A hydrogen strategy for a climate-neutral Europe. [Online]. [14.9.2020] Available: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

European Commission (2020c). Investing in a climate-neutral future for the benefit of our people. [Online]. [5.10.2020] Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0562&from=EN

European Commission (2020d). Sustainable and Smart Mobility Strategy – putting European transport on track for the future. [Online]. [5.10.2020] Available: https://eur-lex.europa.eu/resource.html?uri=cellar:5e601657-3b06-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Environment Agency (2020). Greenhouse gas emissions from transport in EU. [Online]. [11.1.2021] Available: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12

Eurostat (2019). From where do we import energy and how dependent we are? [Online]. [23.10.2020] Available: https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2c.html

Eurostat (2020a). [Online]. [22.10.2020] Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Natural_gas_prices_for_non-household_consumers

Eurostat (2020b). [Online]. [22.10.2020] Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_supply_statistics

Federal Ministry for Economic Affairs and Energy (2020). The National Hydrogen Strategy. [Online]. [5.10.2020] Available: https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

Flowers, S. (2020). Future Energy – Green hydrogen. [Online]. [30.12.2020] Available: https://www.woodmac.com/news/the-edge/future-energy-green-hydrogen/

FCH JU (2019). Hydrogen Roadmap Europe. [Online]. [25.9.2020] Available: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

Gas to Power Journal (2020). Germany prepares to import up to 96 TWh of green hydrogen. [Online]. [5.11.2020] Available: https://www.gastopowerjournal.com/markets/item/11306-germany-prepares-to-import-up-to-96-twh-of-green-hydrogen

Global.Kawasaki.com (2020). World's First Successful Technology Verification of 100% Hydrogen-fueled Gas Turbine Operation with Dry Low NOx Combustion Technology Improving Power Generation Performances to Realize a Hydrogen Society. [Online]. [23.2.2021] Available: https://global.kawasaki.com/news_200721-1e.pdf

Gorre, J., Leeuwen, C. & Ortloff, F. (2018). Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation. Report on the optimal time profile and operation of the conversion technology during a representative year, in the perspective of the available storage capacities [Online]. [28.10.2020] Available: https://www.storeandgo.info/

Green, E. (2018). The use of hydrogen in the iron and steel industry. [Online]. [20.10.2020] Available: https://www.energy.gov/sites/prod/files/2018/08/f54/fcto-h2-scale-kickoff-2018-19-green.pdf

Gupta, R. B. (2009). Hydrogen fuel: Production, transport, and storage. CRC Press. ISBN 9781420045758.

Hamburg, S. (2020). Methane: The other important greenhouse gas. [Online]. [10.10.2020] Available: https://www.edf.org/climate/methane-other-important-greenhouse-gas

Hydrogen Council (2020). Path to hydrogen competitiveness A cost perspective. [Online]. [10.11.2020] Available: https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/

Hydrogen Europe (2019). Hydrogen Europe Vision on the Role of Hydrogen and Gas Infrastructure on the Road Towards a Climate Neutral Economy. [Online]. [5.10.2020] Available: https://ec.europa.eu/info/sites/info/files/hydrogen_europe_-_vision_on_the_role_of_hydrogen_and_gas_infrastructure.pdf

Hydrogen Europe (2020). Green Hydrogen Investment and Support Report. [Online]. [5.10.2020] Available: http://profadvanwijk.com/green-hydrogen-investment-and-support-report/

Hydrogen for Climate Action (2020). 2x40 GW Green Hydrogen Initiative. [Online]. [5.10.2020] Available: https://www.hydrogen4climateaction.eu/2x40gw-initiative

IEA (2014). Hydrogen production and distribution. [Online]. [26.10.2020] Available: https://iea-etsap.org/E-TechDS/PDF/P12_H2_Feb2014_FINAL%203_CRES-2a-GS%20Mz%20GSOK.pdf

IEA (2020). Current limits on hydrogen blending in natural gas networks and gas demand per capita in selected locations. [Online]. [4.2.2021] Available: https://www.iea.org/data-and-statistics/charts/current-limits-on-hydrogen-blending-in-natural-gas-networks-and-gas-demand-per-capita-in-selected-locations

IETA (2020). IETA Annual Sentiment Survey: Carbon price dip to last two years. [Online]. [5.10.2020] Available: https://www.ieta.org/page-18192/9053936

IFAM (2021). Hydrogen-Powered drives for e-scooters. [Online]. [15.2.2021] Available: https://www.fraunhofer.de/en/press/research-news/2021/february-2021/hydrogen-powered-drives-for-e-scooters.html

IRENA (2020). Green hydrogen, electrolysis, ammonia and other e-fuels. [Online]. [24.2.2021] Available:

https://innovationweek.irena.org/-/media/Files/IRENA/Innovation-Week/2020/SessionalSummary/IVIW2020_Session-3_Master-final.pdf

IRENA (2018). Hydrogen from renewable power: Technology outlook for the energy transition, Abu Dhabi, International Renewable Energy Agency. 52 p. ISBN 978-92-9260-077-8

Jovan, D. J. & Dolanc, G. (2020). Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. [Online]. [23.9.2020] Available: https://www.mdpi.com/1996-1073/13/24/6599

Laban (2020). Hydrogen storage in salt caverns [Master's thesis, Delft University of Technology] TUDelft. https://repository.tudelft.nl/islandora/object/uuid%3Ad647e9a5-cb5c-47a4-b02f-10bc48398af4

Lewis, M. (2020). Why the need for green hydrogen points to higher carbon prices. [Online]. [5.10.2020] Available: https://www.ft.com/content/ecdeabd5-e013-44e1-b885-0b7264923e29

Melaina, M. W., Antonia, A., & Penev, M. (2013). Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. [Online]. [3.12.2020] Available: https://www.nrel.gov/docs/fy13osti/51995.pdf

Melaina, M., Penev, M., Steward, D., Antonia, O., Bush, B., Daniel, B., Heimiller, D. & Melius, J. (2012). Hydrogen Infrastructure Cost Estimates & Blending Hydrogen into Natural Ga Pipelines. [Online]. [12.10.2020] Available: https://www.hydrogen.energy.gov/pdfs/htac_nov12_3_melaina.pdf

Menon, E. S. (2015) [Online]. [11.10.2020] Available: https://www.sciencedirect.com/topics/engineering/right-of-way.

Momirlan, Magdalena & T. Nejat Veziroglu (2005). Properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. [Online]. [2.10.2020] Available: https://www.sciencedirect.com/science/article/abs/pii/S0360319904003398?casa_token=npsza0bq5tQAAAAA:C-y__L360uwt1FdVW4hJ2qlQmtc53ZBWmP4_ISK3KtobV4f4psQxU9Tw_Etu0Xxat0ZcFjYTysn-#!

NIST (2015). NIST calculates High Cost of Hydrogen Pipelines, Shows How to Reduce It. [Online]. [11.10.2020] Available: https://www.nist.gov/news-events/news/2015/07/nist-calculates-high-cost-hydrogen-pipelines-shows-how-reduce-it

Radowitz, B. (2020a). BP and RWE plan Germany's first green hydrogen grid. [Online]. [8.10.2020] Available: https://www.rechargenews.com/transition/bp-and-rwe-plan-germany-s-first-green-hydrogen-grid/2-1-775808

Radowitz, B. (2020b). German pipeline operators present plan for world's largest hydrogen grid. [Online]. [8.10.2020] Available: https://www.rechargenews.com/transition/german-pipeline-operators-present-plan-for-world-s-largest-hydrogen-grid/2-1-810731

Rapier, R. (2020). Estimating the Carbon Footprint of Hydrogen Production. [Online]. [11.10.2020] Available: https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/#72e0a31624bd

Rawls, G., Ronevich, J. & Slifka, A. (2017). Lowering Costs of Hydrogen Pipelines through Use of Fiber Reinforced Polymers and Modern Steels. [Online]. [4.4.2021] Available: https://www.energy.gov/sites/prod/files/2017/09/f37/fcto_webinarslides_lowering_costs_h2_pipelines_097217.pdf

Reif, V. & Schittekatte, T. (2020). Electricity markets in the EU. [Online]. [4.2.2021] Available: https://fsr.eui.eu/electricity-markets-in-the-eu/

Snam (2020). Snam and Baker Hughes test world's first hydrogen blend turbine for gas networks. [Online]. [15.10.2020] Available: https://www.snam.it/en/Media/Press-releases/2020/Snam_Baker_Hughes_test_first_hydrogen_blend_turbine.html

Snam, IGU & BloombergNEF (2020). Global Gas Report 2020. [Online]. [16.10.2020] Available: https://www.igu.org/resources/global-gas-report-2020/

Stat (2019). Fossiilisilla polttoaineilla ja turpeella tuotetun sähkön määrä kasvoi 14% v. 2018 – uusiutuvien energialähteiden osuus sähköntuotannosta pieneni.

[Online]. [25.9.2020] Available: https://www.stat.fi/til/salatuo/2018/salatuo_2018_2019-11-01_tie_001_fi.html

Statista (2020). Average grid price of wind energy in the European Union (EU-28) in 2019, by selected country. [Online]. [23.9.2020] Available: https://www.statista.com/statistics/1106870/eu-countries-wind-power-price/

Trinomics (2020). Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans. [Online]. [25.9.2020] Available: https://www.fch.europa.eu/sites/default/files/file_attach/Final%20Report%20Hydrogen%20in%20NECPs%20%28ID%209501746%29.pdf

Tsakiris, A. (2019). Analysis of hydrogen fuel cell and battery efficiency. [Online]. [4.1.2021] Available: https://c2e2.unepdtu.org/wp-content/uploads/sites/3/2019/09/analysis-of-hydrogen-fuel-cell-and-battery.pdf

U.S. Department of Energy (2015). Fuel Cells. [Online]. [25.9.2020] Available: https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

Van Wijk (2019). Hydrogen the bridge between Africa and Europe. [Online]. [11.10.2020] Available: http://profadvanwijk.com/wp-content/uploads/2019/09/Hydrogen-the-bridge-between-Africa-and-Europe-5-9-2019.pdf

Verhelst, S. & Wallner, T. (2009). Hydrogen-fuelled internal combustion engines. [Online]. [2.10.2020] Available: https://www.sciencedirect.com/science/article/abs/pii/S0360128509000422?casa_token=bFcZ1H4DA3oAAAAA:xEeIvyJVNbvk0_iigo2NXR8sC41xF07ap2tiEMrKzuBn3lfzoTzJpXWYT1PqBHWYB_WJ_qHlR9rv

Wang, S. & Jiang, S.P. (2017). Prospects of fuel cell technologies. [Online]. [23.11.2020] Available: https://academic.oup.com/nsr/article/4/2/163/2866463

Watson, F. (2021). EU carbon auction clears at record high price [Online]. [2.4.2021] Available:

https://www.spglobal.com/platts/en/market-insights/latest-news/coal/021621-eu-carbon-auction-clears-at-record-high-price

Westberg, Philip (2020). Development of hydrogen compression ignition engine. [Master's thesis, Aalto University] aaltodoc. https://aaltodoc.aalto.fi/handle/123456789/43534

Willuhn, M. (2020). Green hydrogen to reach price parity with grey hydrogen in 2030. [Online]. [23.9.2020] Available: https://www.pv-magazine.com/2020/07/16/green-hydrogen-to-reach-price-parity-with-grey-hydrogen-in-2030/

Wood Mackenzie (2020). Green hydrogen costs to fall up to 64 % by 2040. [Online]. [20.10.2020] Available: https://www.woodmac.com/press-releases/green-hydrogen-costs-to-fall-by-up-to-64-by-2040/

Wärtsilä (2020). Wärtsilä gas engines to burn 100% hydrogen. [Online]. [22.10.2020] Available: https://www.wartsila.com/media/news/05-05-2020-wartsila-gas-engines-to-burn-100-hydrogen-2700995

Ycharts (2020). European Union Natural Gas Import Price. [Online]. [23.11.2020] Available: https://ycharts.com/indicators/europe_natural_gas_price