MSc Program
Renewable Energy Systems

The Potential of Combined Electricity and Hydrogen Generation in the Energy System: The Case of the Slovak Republic

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 04.11.2020

Affidavit

I, **MGR. JÁN WEITERSCHÜTZ**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE POTENTIAL OF COMBINED ELECTRICITY AND HYDROGEN GENERATION IN THE ENERGY SYSTEM: THE CASE OF THE SLOVAK REPUBLIC", 90 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 04.11.2020

Signature

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Abstract

The European Commission announced that the 37% funding was going to be invested in the European Green Deal objectives, including one of the “lighthouse” European project – hydrogen. The deeper decarbonisation requires the broader use of renewable energy and renewable hydrogen. It should lead to a half capital cost reduction of electrolysers in 2030. Slovakia has three problems that can be solved by hydrogen. CO_2 emissions, poor air quality and problematic integration of the variable renewable sources. Hydrogen has the potential to solve all three problems not only in Slovakia, however, globally. The main objective of this master thesis is to assess the ability of a large-scale Power-to-Hydrogen plant to generate the renewable electricity to the grid, when it is needed, for the market price and to produce the renewable hydrogen, when the electricity demand is low, in order to make the renewable hydrogen commercially competitive. The synergy between the variable renewables and the electrolysers offers production-side flexibility that allows to transform the variable renewables to the flexible ones and to replace the fossil-based hydrogen by the renewable one in the industry, mobility and heating. The purpose of this thesis is to provide the overview of the role of hydrogen to decarbonise the energy systems, to explain the reasons why Slovakia lags the binding renewable energy targets for 2020 and to propose a hydrogen way to meet the national objectives in 2030. The thesis also estimates the hydrogen deployment potential in Slovakia, it counts both the current and the future demand for the renewable hydrogen and estimates the adequate capacity of the renewable energy sources needed for the renewable hydrogen production. Finally, the case study assesses a 150 MW wind farm directly supplying the 50 MW electrolyser with the renewable electricity in three different demand-supply scenarios in the conditions of the south-west Slovakia. In all scenarios, the retrospective simulation is used to prove that the renewable hydrogen can be produced without subsidies under the price of € 4/kg based on the market prices in 2019. Results show that the wind farm in the low wind conditions is profitable without the need of any subsidies, however, the fixed minimal price is needed to avoid more and more often curtailments. The electrolyser can offer this minimal price through the fixed electricity purchase contract. However, the electrolyser is not able to produce hydrogen under the price of € 4/kg in any of 3 the assessed scenarios. The profitable operation without the side earnings requires a capital expenditure subsidy on electrolyser of 23% - 42% depending on the scenario.

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1 Introduction

In September 2020, Ursula von der Leyen, the President of the European Commission, held a speech about the state of the European Union in 2020. Among other targets, she proposed to increase the CO_2 reduction target from 40% to at least 55% for 2030. European Parliament raised the target even higher, calling for a reduction of 60% in 2030, adding that national targets shall be increased in a cost-efficient and fair way. The European Commission announced that 37% of funding would be invested in the European Green Deal objectives, including one of the "lighthouse" European projects – hydrogen.

Deeper decarbonisation requires broader use of renewable energy and renewable hydrogen. The Hydrogen initiative 2x40 GW has become a part of The European Clean Hydrogen Strategy, where massive support for 40 GW electrolysers by 2030 in the EU has been announced. It should lead to a 50% capital cost reduction of the electrolysers in 2030. The large-scale integration of both cost-effective and variable renewables brings production-side flexibility rather than costly and limited ancillary grid services. Along with the long-term cost reduction of PV and wind farms, clean hydrogen should become competitive compared to fossil-based hydrogen after 2030. There are many hydrogen labels according to the method of production and the carbon footprint. The official labelling of hydrogen for the EU countries published by the European Commission explains Appendix 1.

The Slovak Republic, as a member of the EU, can benefit from the massive support of the European Commission to build a complex hydrogen value chain. The chain starts with the clean hydrogen production from renewables. The Proton Exchange Membrane (PEM) electrolysers as a new technology in the market give a chance to meet the climatic targets and to improve the quality of air cost-effectively. Thus, renewable hydrogen can make Slovakia a better, safer and healthier place for living.

The new Slovak government have chosen the hydrogen value-chain deployment as one of its primary tasks. Besides the climate and energy benefits, hydrogen can create many new jobs and strengthen the national energy security. I am honoured to work with the Slovak Ministry of Economy to develop the National Hydrogen Strategy, where the production of renewable hydrogen would have a strong position.

1.1 Motivation

Slovakia has three significant challenges that can be solved by hydrogen: CO_2 emissions, poor air quality and complicated integration of the variable renewable sources. Currently, Slovakia faces the legal action of the European Commission for exceeding the local air pollution limits. Therefore, Slovakia must find some practical solutions to reduce air pollution, especially in the cities and agglomerations. Clean urban transport with almost zero emissions can avert this threat and improve the environment for citizens. Moreover, clean hydrogen could play a crucial role in improving local air quality. The synergy between the variable renewables and electrolysers offers the production-side flexibility that allows to transform the variable renewables to the flexible ones and to replace the fossil-based hydrogen by the clean one in the industry, mobility and heating. Hydrogen, as a carbon-free energy carrier has the potential to solve all three issues not only in Slovakia but globally. However, currently, there is no facility in Slovakia producing renewable hydrogen. Thus, this master thesis evaluates a deployment potential of the combined electricity and hydrogen production from the variable renewables.

There are three main questions that this thesis aims to answer. **The first question is how a Power-to-Hydrogen plant can contribute to integrating the future large-scaled PV and wind plants to the energy system.** The goal is to operate an on-site hydrogen production and a flexible on-demand power generation in the scale of hundreds of MW. In other words, this thesis evaluates how to allow a cost-effective deployment of the variable sources of the renewable electricity in Slovakia without any negative impacts on the power grid and to utilise the potential to decarbonise the economy as effectively as possible. The Power-to-Hydrogen solution should simultaneously offer a competitive price of green hydrogen as a carbon-free fuel to the transport sector and as a feedstock to the chemical industry.

This thesis intends to find out an answer if the large-scale electrolysers connected directly to the on-site renewable electricity sources, such as a wind farm, could turn the variable power generation into wanted and predictable operation without any negative impacts to the power grid. A detailed discussion can be found in Chapter 6 about how the production-side regulation can accelerate a broader deployment of variable renewables.

The second question is how to achieve the sustainability of a Power-to-Hydrogen plant without subsidies. This question generates two more sub-questions.

a) **What should be the price of electricity generated from the wind farm providing electricity for the electrolysis producing hydrogen for the price of 4 EUR / kg H_2, so that the Renewable Electricity Source (RES) and the Electrolyser (EC) remain profitable?** Executing the internal analysis with the representative of the national railway transport operator, the Railways of the Slovak Republic (ZSSK), the cost of hydrogen in the amount of € 6/kg of H_2 is a competitive price which allows replacing the regional diesel trains by the fuel cell trains, providing the cost for distribution and refuelling infrastructure is not higher then € 2/kg of H_2.

b) What is the optimal operational model from both the technical and economic point of view in order to achieve a profitable operation?

Finally, the third question is: **What are the main barriers that currently prevent successful implementation of the variable renewables on the market?**

1.2 Major References

There are four major references used to develop a qualitative research for the second part of this work. This thesis draws information from the literature referring this topic, e.g.: (Lappalainen, 2019). His master thesis with the title "Techno-economic Feasibility of Hydrogen Production via Polymer Membrane Electrolyte Electrolysis for Future Power-to-x Systems". Lappalainen discussed the hydrogen production via a proton exchange membrane electrolyser. He examined the hydrogen as an energy carrier, the main production methods and the delivery and the end-use applications. He presented the technology and operation strategies. He compared the production costs of two production methods: the SMR and the alkaline electrolysis one. In the practical part, his thesis is divided into a technical evaluation of the pilot-scale PEM electrolysis operation and the economic calculations of the feasible operation frameworks for the PEM electrolysis in Finland. The results from the operation of the pilot-scale PEM electrolyser showed excellent dynamic properties and a stable, independent hydrogen production. The economic calculations showed that only the Speculative 2030 scenario with the FCR-N is feasible without any raised prices of hydrogen and oxygen. In the case of higher prices of hydrogen and oxygen, all scenarios become profitable.

(van der Roest *et al.*, 2020) in the journal article *"…proposed a concept for a neighbourhood where locally produced renewable energy is partly converted and stored in the form of heat and hydrogen, accompanied by rainwater collection, storage, purification and use (power-to-H3). A model is developed to create an energy balance and perform a techno-economic analysis, including an analysis of the avoided costs within the concept. The results show that a solar park of 8.7 MWp combined with rainwater collection and solar panels on roofs, can supply 900 houses over the year with heat (20 TJ) via an underground heat storage system as well as with almost half of their annual water demand (36,000 m^3) and 540 hydrogen electric vehicles can be supplied with hydrogen (90 tonnes). The production costs for both hydrogen (€ 8,7/kg) and heat (€ 26/GJ) are below the current end user selling price in the Netherlands (€ 10/kg and € 34/GJ), making the system affordable. These results make clear that it is possible to provide a neighbourhood with all these different utilities, completely based on solar power and rainwater in a reliable, affordable and clean way."*

A study commissioned by the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) in consultation with the European Commission – DG Energy focuses on the Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans. "*The study analyses the role of hydrogen in the National Energy and Climate Plan (NECP) of Slovakia and identifies and highlights opportunities for hydrogen technologies to contribute to effective and efficient achievement of the 2030 climate and energy targets of the EU and its Member States... The study focuses on the potential and opportunities of renewable hydrogen, produced by electrolysers using renewable electricity and of low-carbon hydrogen, produced by steam methane reforming (SMR) combined with carbon capture and storage technology.*" The opportunities for and impact of hydrogen deployment are assessed in Slovakia currently.

1.3 Aims and Structure of the Thesis

This thesis aims to provide an overview of the role of hydrogen to decarbonise the energy systems, to explain the reasons why Slovakia lags in meeting the binding renewable energy targets for 2020. The thesis proposes a hydrogen way to meet the national objectives in 2030. It also estimates a hydrogen deployment potential in Slovakia, it evaluates the current and future demand for the clean hydrogen and estimates the adequate capacity of the renewable energy sources needed for the clean hydrogen production. Finally, the case study assesses a 150 MW wind farm directly supplying a 50 MW electrolyser with the renewable electricity in three different demand-supply scenarios in the conditions of south-west Slovakia. In all the scenarios, the retrospective simulation is used to prove if the clean hydrogen can be produced for the price in the amount of € 4/kg of H_2 without subsidies. In general, the aim is to evaluate the ability of the Power-to-Hydrogen plant to boost the development of renewables to supply the clean hydrogen production by the renewable electricity without a negative impact on the power grid and consumers. The appraisal of the business model will show the ability of replication of the Power-to-Hydrogen plant design within the other EU countries.

This Master Thesis serves as an overview of the current status and perspectives of the renewable energy sector in Slovakia. It explains why Slovakia has a problem meeting the 2020 renewable targets and how the politicians want to achieve the 2030 ones. It also explains in detail the role of hydrogen in the global low-carbon energy system and in the carbon-neutral economy in Slovakia. This work evaluates the combined renewable power and clean hydrogen production in a Hybrid Solar and Wind powerplant equipped by the water electrolyser. It also analyses a concrete business case of the renewable power generation and the clean hydrogen production in the conditions of a real site in south-west Slovakia.

The thesis is divided into the chapters as follows:

Chapter 1 contains the introduction, motivation and reason why I chose this topic. Then it contains the formulation of the research problem which will be further analysed and dealt with.

Chapter 2 describes the methodological procedure used in this thesis. The use of the qualitative type of research is based on the interviews with experts in the field of energy, hydrogen, transport or industry, expert studies, and even webinars, because during a coronavirus pandemic, more and more hydrogen experts use this method to present their research rather than to write books or academic papers.

Chapter 3 evaluates the contemporary status of the renewable sector in Slovakia. The reasons why Slovakia is falling behind the trajectory of the share of the renewable energy in gross final energy consumption will be analysed afterwards. The RES targets 2030 in the Slovak Energy and Climate Plan will be assessed next, followed by the analysis of the hydrogen potential in reaching the renewable objectives of the Plan.

Chapter 4 explains the role of hydrogen in the low-carbon energy system. It presents the basic hydrogen specifications, compares the different ways of the hydrogen production and outlines the current status and prospect of the hydrogen technologies. The appraisal of hydrogen as the versatile energy carrier for the sector coupling follows. The chapter introduces seven roles of hydrogen in the low-carbon energy system, meeting the climate targets.

Chapter 5 focuses on the ability of hydrogen to decarbonise the Slovak economy. It identifies the current and future hydrogen consumers. It assesses the hydrogen needs in the industry, heating and the transport sector in 2030. It analyses the needful capacity of the new RES to cover the future demand of the clean hydrogen.

Chapter 6 performs a technical-economic appraisal of the case study – a 150 MW Power-to-Hydrogen plant in the south-west Slovakia. The technology overview explains the structure and principles of the operation of the Power-to-Hydrogen plant. The synergy between RES and EC through the overpowering strategy and three different supply-demand scenarios will be described below. The chapter provides a dynamic investment analyses of a wind farm as the source of the green electricity and a PEM electrolyser as the generator of the clean hydrogen, heat and oxygen. The retrieved data will be used in order to design an optimal operational regime of the Power-to-Hydrogen plant.

Chapter 7 summarises the results reached throughout the research.

Chapter 8 contains the conclusion, including the suggestions for removing the main barriers hindering the deployment of the Power-to-Hydrogen plants. It also contains the recommendation for the optimal model of the Power-to-Hydrogen plant operation in order to reach a successful RES integration to the energy system of Slovakia. The chapter provides the recommendation of the most suitable operational model of the Power-to-Hydrogen plant based on the most valuable scenario. It identifies the opportunities for the future more profitable operation. It proposes suitable locations at the end based on the identified placement criteria.

2 Method of approach

The combination of the qualitative and quantitative research methodological approach was chosen in this master thesis. For the evaluation of the renewable energy sector in Slovakia in chapters 3-5, a qualitative methodological approach was used. The information about the current status of the renewable support and the upcoming market-oriented support was collected from the web pages of the ministries, regulatory authorities and the European Commission. The same approach is applied in the next chapters, where the role of hydrogen in the low-carbon energy system is assessed. Predominantly the secondary data of the existing knowledge were gathered through the literature study. The retrieval of information from different sources ranging from the studies, reports, journals, websites, books, research papers, white papers, reports, journals and discussions with experts has been used in this thesis. In the subchapter about the potential of the production and use of the clean hydrogen in Slovakia data from the personal interview were used. The interview took place in Bratislava in 2019 with the representatives of the Slovak Ministries and partners within the working group for the Revision of the Framework of the Alternative Fuels where I personally participated as the representative of the Slovak Hydrogen Association.

For the construction of the technical and economic case of a 150 MW Power-to-Hydrogen plant in chapter 6 the quantitative research methodological approach was chosen. The Power-to-Hydrogen plant consists of two units: a wind farm, a renewable electricity source (RES) and a PEM electrolyser (EC). The wind farm supplies the EC by the renewable electricity. The EC produces the clean hydrogen from the renewable electricity. The capacity factor of the EC directly depends on the capacity factor of the RES. No electricity will be used from the grid other than electricity to provide support services for the national Transmission System Operator (TSO). The methodical approach of the case study describes the case structure diagram in Figure 1.

In order to perform a detailed research, the actual technical and economic input data for both RES and EC was used as an input for calculations.

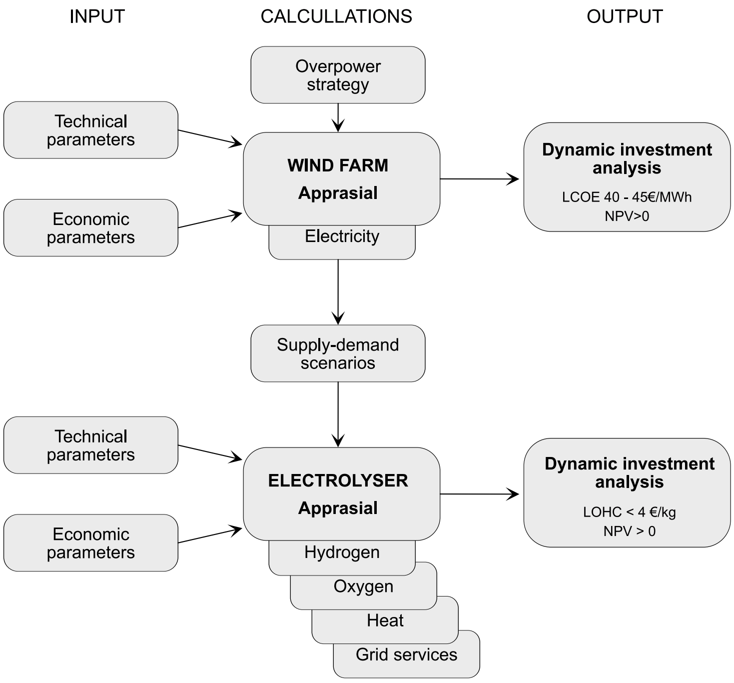

Figure 1: The Diagram of a Power-to-Hydrogen plant case structure (own diagram)

For the **wind farm appraisal**, the Danish developer Eurowind energy S/A offered the verified technical specifications of the large low-wind on-shore turbines. A real year-round wind measurement has been retrieved from the Slovak company Solarenergia to calculate an hourly electricity generation. One of the often-applied method how to increase the EC capacity factor is the RES overpowering compared to the nominal power of EC. Therefore, this strategy causes that during the windy hours, the wind farm delivers the electricity to the EC at the maximal nominal power and the surplus electricity to the grid, or directly to the consumer. This calculation assumes the grid delivery only. Then the calculation performs a simulation of the hourly electricity distribution to the EC and the grid using the actual spot-market power prices from 2019. The simulation analyses 3 supply-demand scenarios in order to recommend the optimal scenario. Afterwards, the dynamic investment analysis assumes that the investment horizon is 20 years, and the discount rate (weighted average cost of capital [WACC]) is 7,5%. Finally, the net present value and the long run generation cost unveil the performance of the wind farm.

Concerning the **electrolyser appraisal**, the input data have been collected mainly from the reports of a number of reputable hydrogen and energy agencies and consulting companies. Some of the most valuable inputs, such as the specific investment costs, have been obtained during the personal consultations with Sophie Eynon, the consultant of the Element Energy, Peter Hegeduš, the President of the

Slovak Hydrogen Association, and Alexandru Floristean, the legal and project manager of Hydrogen Europe. Then technical specifications of the PEM electrolyser are evaluated followed by the technical and economic appraisal for each of the final products from the EC, such as hydrogen, oxygen, heat and the ancillary services provided for the TSO. At the end of the EC appraisal, the dynamic investment analysis is performed with the same investment horizon of 20 years and a discount rate of 7,5%. Finally, the net present value and the levelised costs of hydrogen unveil the performance of the electrolyser too.

3 The Renewable Energy Sector in Slovakia

For a better understanding of the problem with the integration of the large variable renewables into the Slovak electricity systems, firstly, the start of the deployment of the renewables must be explained. The massive deployment of the first large-scale renewables, the Photovoltaic plants (PV plants), began ten years ago. The first large PV plants (up to the 4-MW ones) were put in operation in 2010 in Slovakia. The Slovak government have chosen the feed-in-tariff incentives for 15 years without indexing. The generous subsidies attracted many investors and the annual increase in the installed power, especially in photovoltaics, exceeded the expectations of the Ministry of Economy of the Slovak Republic. Since then, the Slovak government and the national transmission grid operator faced the issue of how to integrate the solar and wind farms without any negative impacts on the power grid and the customers' electricity bills. A solution has been found quickly. The development of wind farms has been stopped in the beginning. Therefore, Slovakia has only five wind turbines in operation today. The distribution system operators stopped the deployment of the PV plants and the small hydropower plants in 2014 after the Slovak TSO had published the conclusions of the impact of the renewable electricity sources operated in the Slovak Republic on the Slovak electricity system. According to the TSO "*…it is necessary to point out that, in contrast to the current situation, when the installed capacity of 480 MW has already been built and put into operation in the power plants, it is not possible until the end of 2016, resp. until the period of further increase of transmission capacity on the Slovakia - Hungary profile, consider further construction of RES (even within the scope of the remaining rest of the National Action Plan of the Slovak Republic)*" (SEPS, 2012).

Since 2014 no PV plant larger than 10 kW and no wind turbine has been connected to the grid with the Feed-in Tariff (FIT). The mentioned situation remained the same till the end of 2018 when the FIT system finished, and the Auction system based on more market-oriented Feed-in Premium (FIP) incentives began.

Nowadays, there are two real obstacles in meeting the national targets referring the renewables. Firstly, today more than 540 MW of the large PV plants is in operation, and their installing power ranges from 100 kW to 4 MW. The above-mentioned plants face the challenge of the future profitability after their FIT support expires throughout 2025 - 2027. Secondly, the Slovak government in the National Climate and Energy Plan (NECP) set the new RES targets for 2030, in line with the EU targets, where the share of RES on the net domestic energy consumption should rise from 14% to 19,2%, as Figure 1 exhibits. The scissors are opening, and the threat of lack of RES to meet the 2020 target is real.

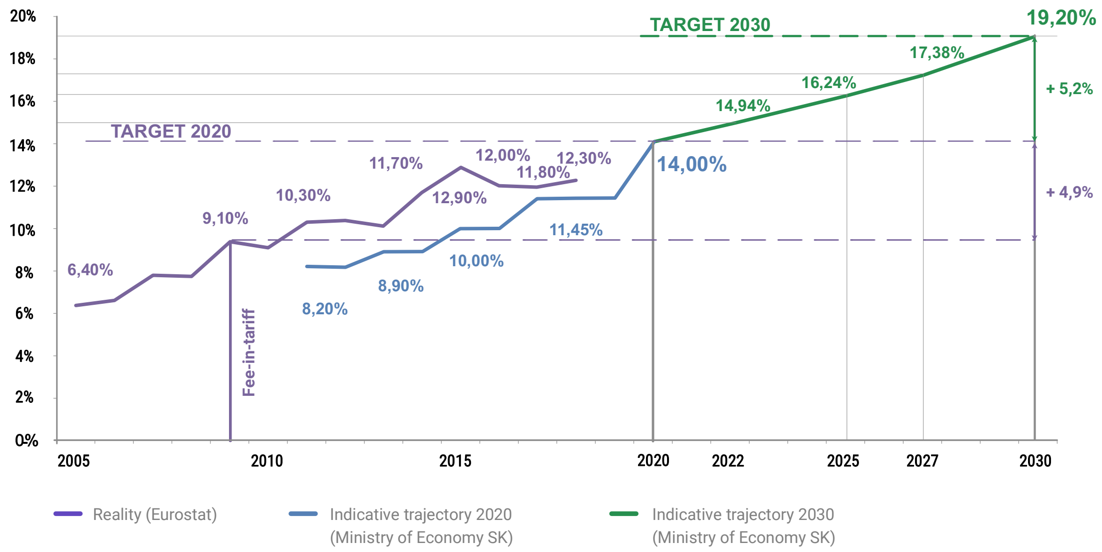

Figure 2: The Share of the Renewable Energy within the Net Final Energy Consumption in Slovakia (own graph based on Ministry of Economy SR, 2020)

The National Support Schemes

In 2019, the long-awaited amendment to the RES Support Act no. 309/2009 came into force (SlovLex, 2020). The Ministry of Economy of the SR has reformed the system of support for RES and the highly efficient combined heat and power generation.

The new support scheme promotes the market-based approach in line with the EU guidelines on the national aid for the environment and energy. The revision does not only address the change in the support system, but also introduces the institute of a local source, the tariff for the system operation compensation for the large industrial customers over 1 GWh of the annual consumption, the unauthorised supply to the system, and it legalises the payment of the G-component.

The above-mentioned Ministry of Economy justifies the change of the support system mainly due to the advanced maturity phase of the renewables.

The whole support system for RES is under the patronage of a state company, the Organiser of the Short-term Electricity Market (OKTE). This entity must guarantee the centralisation of the administration and financing, the reduction of the administrative costs, the costs of forecasting and the management of the deviation.

The new support system maintains the priority connection, the access to the grid and the distribution of electricity for the newly installed RES. The reform of the RES support scheme can be divided into two groups.

(1) Feed-in-tariff for RES up to the rated capacity 500 kW and

(2) Feed-in-premium for the larger RES over 500 kW and all PV and wind installations over 10 kW.

1a) The producers of the renewable electricity (RE) are entitled to receive a supplement, to purchase all the electricity except the power during the negative price on the market, to transfer the responsibility for the deviation. Only the producers of the electricity with the installed capacity of up to 250 kW, producing electricity from water, geothermal energy, biogas, landfill gas, gas from the wastewater treatment plants and the highly efficient combined heat and power plants, are eligible to receive this support. This scheme is effective not later than on 31 December 2033. The maximum duration of the support is limited to 15 years from the date the RES was put into operation.

(1b) The RES with the installed capacity from 251 to 500 kW producing electricity from water, geothermal energy, biogas, landfill gas, and gas from the wastewater treatment plants up to 1 MW are entitled to a surcharge. The RES will have to sell the produced electricity to a chosen trader and will not be responsible for the deviation. This type of aid applies for 15 years from the date on which the installation was put into operation.

The amount of the surcharge will, as before, represent the difference between the price of electricity in the Price Decision and the price of the purchased electricity set annually by the Regulatory Office for Network Industries (RONI) until 30 June.

(2) The new Feed-in-Premium system applies to the facility of the producer of electricity with the total installed capacity from 10 kW to 50 MW as a result of the auction announced by the Ministry of Economy. The Ministry of Economy will decide which technology it will be interested in and what volume of electricity from RES it will need. This type of aid applies for 15 years from the date of the commissioning of the installation. The amount of the surcharge will represent the difference between the winning price set in the auction and the market price of electricity. The producers must place electricity on the market separately via a chosen trader. They are responsible for the deviation. The purchase price is one of the main decisive factors for all the producers, on which the surcharge depends. The purchase price will be determined annually by RONI as the assumed market price of electricity (adjusted by a coefficient) and not as the price for losses - the arithmetic average of the price of electricity for the losses of the three regional utilities.

Today the renewables are more often facing to periods with the negative prices of electricity on the market when the RES may not deliver electricity to the grid. The support will not be granted to the producers which constitute an island operation and are therefore permanently disconnected from the distribution system.

The Ministry of Economy announced the first auction in February 2020. However, the auction has not taken place yet. Due to the epidemiological situation caused by the coronavirus, the Ministry postponed the auction to the end of 2020. The Ministry is currently preparing legislative amendments for the better RES support.

Most likely, the introduction of the auction system will increase the competitiveness of the electricity producers, as the competition between them will intensify. In terms of costs, as well as the administration of the electricity system, auctions appear to be a more advantageous system than a guaranteed price for the indefinite number of the electricity producers. The state thus gained more robust control over the development of RES.

It will be essential to set the auction volume in line with the expected demand and not to create unnecessary barriers referring the development of the competition. According to the experience of the western EU countries, the higher efficiency and financial savings have been confirmed in the auction schemes compared to the system of the fixed guaranteed prices.

National Energy and Climate Plan 2030

In December 2019, The Slovak Ministry of Economy published the National Energy and Climate Plan, in which it defines the new targets for 2030 as follows: "*The main quantified NECP targets for the SR by 2030 are to reduce greenhouse gas emissions for sectors not involved in emissions trading (non-ETS) by 20% (the share has been increased from the originally declared 12%). The RES share in final energy consumption has been set at 19.2% for 2030, together with meeting the required target of 14% of RES in transport. The elaborated measures to achieve the national contribution of the SR in energy efficiency show slightly lower values (30.3%) than the European target of 32.5%. Industry and buildings will be key to achieving the targets. The interconnectivity of the electricity grids is already above 50% and will remain so in 2030, so the target of at least 15% will be met.*" (Ministry of Economy of the Slovak Republic, 2019a: 8, 9). Table 1 summarises the NECP targets as follows.

Table 1: Europe-wide and National Targets. Source: (Ministry of Economy of the Slovak Republic, 2019a: 8, 9)

EU and SR targets	EU 2030	SR 2030
Greenhouse gas emissions (compared to 1990)	-40%	*
Emissions in the ETS sector (compared to 2005)	-43%	
Non-ETS greenhouse gas emissions (compared to 2005)	-30%	-20%
Total share of renewable energy sources (RES)	32%	19,2%
Share of RES in transport	14%	14%
Energy efficiency	32,5%	30,3%
Interconnection of electricity systems	15%	52%

*There are no national targets for individual Member States

The Hydrogen Deployment according to NECP

In August 2020, The Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a public-private partnership supporting the research, technological development and the demonstration activities in the fuel cell and hydrogen energy technologies in Europe published a study analysing the role of hydrogen in the **National Energy and Climate Plans**. The FCH JU identified the opportunities for the hydrogen technologies to contribute to the effective achievement of the 2030 national climate and energy targets. The study focuses on the potential and opportunities of the renewable hydrogen, produced by the electrolysers using the renewable electricity and the low-carbon hydrogen, produced by the steam methane reforming combined with the carbon capture and storage technology. The study discusses the estimation that by 2030 around 1% of its RES targets for the transport sector will be covered by the direct use of hydrogen (2 ktoe hydrogen out of the total of 229 ktoe renewable fuels) in Slovakia. By 2040, this share could be multiplied by more than 20. Slovakia addresses the entire value chain from the generation of hydrogen, over the underground storage, to the refuelling infrastructure to the end applications mainly both in the transport sector and the industry. To cover the estimated hydrogen demand from the new hydrogen applications and the fossil hydrogen substitution, from 330 to 900 MW of the dedicated renewable electricity capacity to produce the green hydrogen by the electrolysis should be installed. While the surplus electricity may be available at the time of the high electricity production from the renewable sources, the bulk will have to be covered by the dedicated resources. In these two scenarios, by 2030 part of the demand for hydrogen would still be covered by the fossil hydrogen produced by the reformation of the fossil fuels with the steam methane (FCH JU, 2020: 6–8).

In its NECP, in 2030 Slovakia estimates the installed capacity of 0,5 GW in the wind and 1,2 GW in the solar PV plants, which will produce 2,3 TWh (1T Wh wind and 1,126 TWh) of the variable renewable electricity in 2030 (Ministry of Economy of the Slovak Republic, 2019a: 45). However, the technical potential of the renewable electricity production in Slovakia is significantly higher (Figure 3). The main portion takes the onshore wind with the power generation of 50 TWh which corresponds to the installed power of 17,8 GWh. PV could generate10 TWh of the greed electricity corresponding to the 7,9 GW installing power. Thus, the technical potential of the variable electricity generation in Slovakia is about 60 TWh, which means 25,7 GW of the installed power in the conditions of Slovakia.

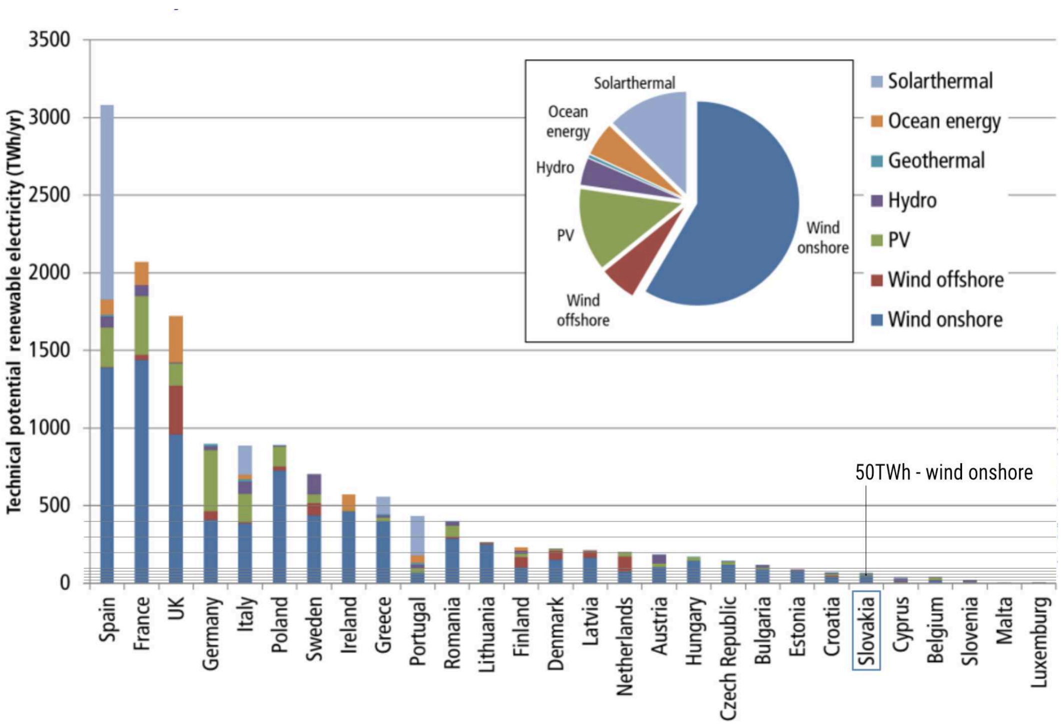

Figure 3: The EU Renewable Electricity Generation Potentials by the Member States. The Average of Ranges per the Member States. Source: (Nuffel et al., 2019: 7)

4 The Role of Hydrogen in the Low-carbon Energy System

This chapter is dedicated to a discussion about hydrogen as a future key player while decarbonising the energy and transport sector. It describes the essential characteristics of the lightest and most abundant element in the Universe and explains the production of hydrogen. The next subchapter surveys the seven roles of hydrogen in the carbon-neutral energy system and appraises the potential of the green hydrogen in the Slovak conditions.

4.1 Hydrogen

Hydrogen is the lightest and the most abundant element in the Universe with a high calorific value. However, on Earth, hydrogen binds to the other elements in the compounds, so it hardly occurs in a pure form. The production of the pure hydrogen is an energy-intensive process and the external energy must be used to split the hydrogen compounds.

Hydrogen has various end-use applications and if it is produced using the renewable energy, it has a potential to make significant reductions in the CO_2-emissions in the energy sector, limiting the global temperature rise.

Hydrogen is odourless, colourless, and tasteless non-toxic gas in the standard temperature and pressure conditions (STP) 273,15 K and 1 bar with high energy content: 142 MJ/kg Higher Heating Value (HHV) and 120 MJ/kg lower heating value (LHV). The difference between the HHV and LHV values is molar enthalpy when water vaporises (44,01 kJ/mol) (Lappalainen, 2019: 4). Basic physical properties of hydrogen are accessible in Table 2.

Hydrogen is the lightest gas with a density of 0.0899 kg/m^3 under the STP conditions. In most cases this is a major disadvantage, making hydrogen storage more complicated. Therefore, it is traditionally pressurized or liquefied in order to store the reasonable amounts of energy. Figure 4 clarifies how the hydrogen density depends on the temperature and pressure. The highlighted areas in the graph refer to the practical cases of the particular ways of hydrogen storages in the forms of hydrogen as follows: the pressurized, liquefied, and the cryo-compressed. For example, when the personal FCEV use tanks with the compressed hydrogen up to 700 bar, the density of hydrogen is 40 kg / 1 m^3. Thus, they store approximately 5 kg in the tank of the car in the volume of 125 l. Furthermore, many other storage methods are being developed including the materials-based technologies which include the metal hydrides, liquid organic hydrogen carriers (LOHC) and sorbents (MOFs, Zeolites, Nanotubes) (Shell, 2017: 13).

Table 2: The Hydrogen Physical Properties. Source: (Lappalainen, 2019: 6)

Heating values	HHV: 142 MJ/kg (39,4 kWh/kg) LHV: 120,0 MJ/kg (33,3 kWh/kg)
Density	0.0899 kg/m3
Boiling point	20,27 K
Melting point	13,99 K
Lower and upper flammability limits	LFL: 4 % UFL: 75 %
Autoignition temperature	773 - 850 K

Hydrogen has high diffusivity and can leak through the porous materials and some type of metals. Pressurized cisterns with an inner insulating layer are suitable for the storage in the small- and mid-scale applications. They offer an affordable price, safety, and high cycling rate.

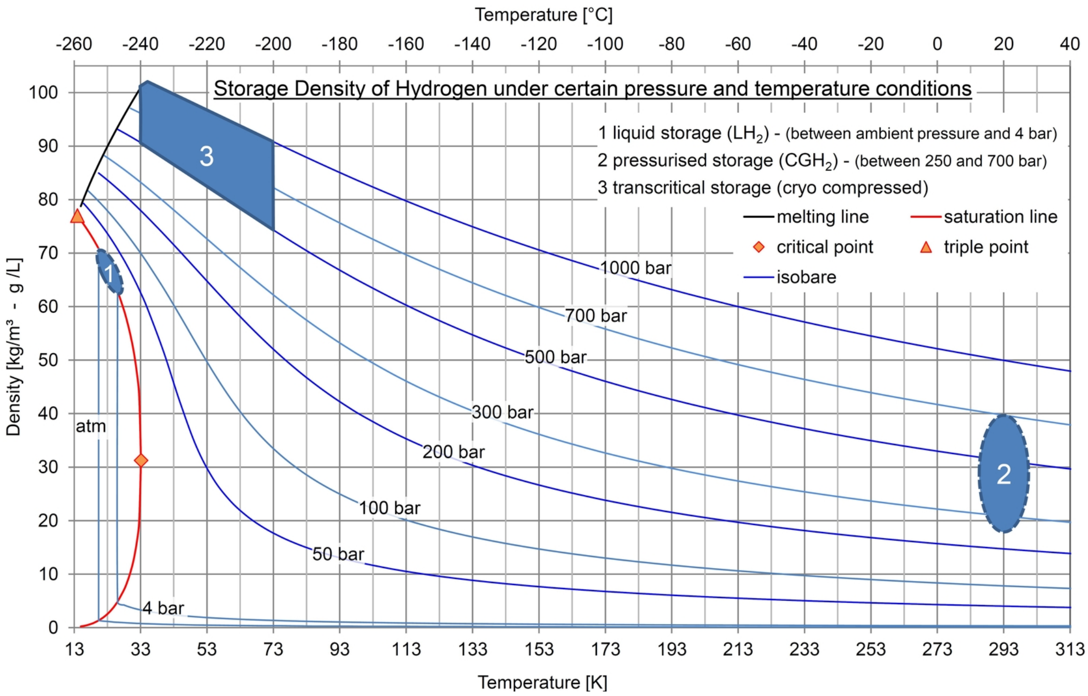

Figure 4: The Density of Hydrogen under the Different Temperature and Pressure Conditions. Source: (ILK Dresden, 2020)

When handling hydrogen, its flammability range from 4 - 74 % in the air must be considered. On the other hand, if it remains in a well-ventilated area, there is no risk to attain this limit, however, the limits grow with the temperature. Luckily, hydrogen has a relatively high autoignition temperature of 773 - 850 K for the stoichiometric hydrogen in the air (Ordin, 1997: 214). The autoignition temperature varies in the literature as the temperature is dependent on the system factors. The hydrogen’s low density makes it safer because it does not collect near the ground, but dissipates quickly in air in case of leakage (Lappalainen, 2019: 6). Unlike the air, under the normal conditions, hydrogen heats up as it expands, so a negative Joule-Thomson coefficient must be considered. When the temperature drops below 202 K, hydrogen returns to the typical Joule-Thomson phenomenon (Shell, 2017: 9).

4.2 The Production of Hydrogen

Hydrogen can be produced from a variety of sources, including the fossil fuels such as natural gas and coal, or biomass, non-food crops, nuclear energy and renewable energy sources such as wind, solar, geothermal and hydropower, as Figure 5 showes. Moreover, the chlorine and caustic soda production generates hydrogen as a by-product. This wide range of potential sources is the reason why hydrogen is such a promising energy carrier. Although it is cheaper to produce hydrogen today through a more CO_2-intensive process called SMR, hydrogen can also be produced by a process that uses the renewable electricity, leading to the production of the green or blue hydrogen (Hydrogen Europe, 2020b). Today, the need for an energy transition towards a cleaner, more sustainable energy system is widely accepted.

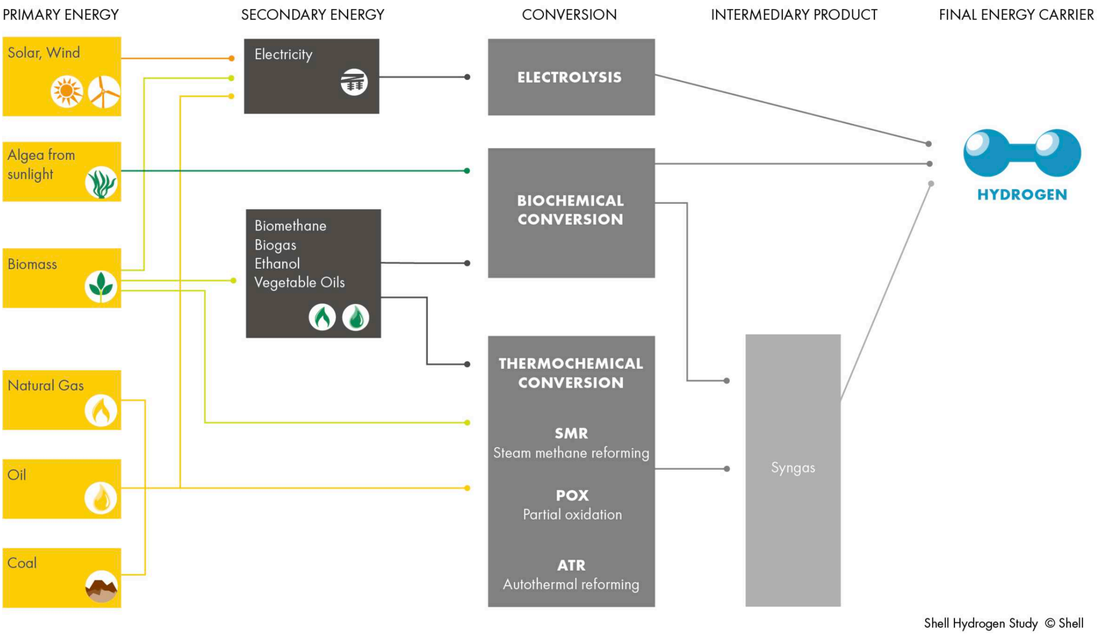

Figure 5: The Processes of the Production of Hydrogen. Source: (Shell, 2017:12)

The global hydrogen production capacity has been estimated at 70 Mt annually. Today, 76% of hydrogen is produced from natural gas and nearly all the rest (22%) from coal. The annual hydrogen production requires 6% of global natural gas use, approximately 205 billion m^3 of natural gas and 107 Mt of coal, 2% of global coal use. The water electrolysis counts for 2% of global hydrogen production. As a result, the current global hydrogen production is responsible for 830 Mt CO_2 per a year (IEA, 2019: 37).

Total hydrogen production capacity in the European countries at the end of 2018 has been estimated at 11,5 Mt per a year. Excluding the coke oven gas hydrogen from this, the remaining hydrogen generation capacity is around 9,9 Mt per a year (FCH 2 JU, 2020: 3).

The hydrogen production in Slovakia, exclusively for the industrial use, achieves around 0,2 Mt of hydrogen annually. The ammonia plant Duslo and the refinery Slovnaft use natural gas for the hydrogen production. In these cases, hydrogen acts as a feedstock to produce the final products. Approximately 1950 t of hydrogen per a year is produced as a by-product from the chlorine-alkali electrolysis in the Fortischem plant. US Steel Košice, the large steelmaker, uses hydrogen as coke oven gas today. Chapter 5 deals with the hydrogen potential for decarbonisation of the Slovak economy.

4.3 The Sector Coupling

A schematic diagram of the present energy system and a potential future low-carbon energy system can be seen in Figure 6. In the current energy system few links exist between the different transmission and distribution (T&D) systems. While today's system is based on the fossil fuels, in a future system, hydrogen could link the different infrastructural networks in a low-carbon energy system. The future hydrogen-based system will supply buildings, industry, transport, and mainly the T&D of electricity. It could also deliver heat and fuels in liquid as well as gaseous form via different energy networks (OECD/IEA, 2015: 10).

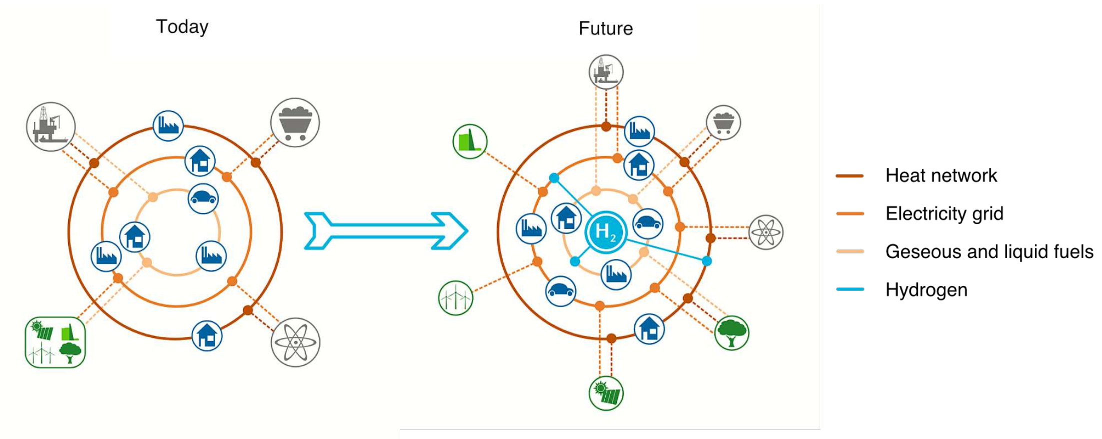

Figure 6: The Energy System Today and in the Future. Source: (IEA, 2015: 10)

From a technical point of view, hydrogen could become a missing link in the energy transition. "*Hydrogen from the renewable electricity allows large amounts of renewable energy to be turned from the power sector into the sectors for which the electrification and hence decarbonisation is otherwise difficult, such as transport, buildings and industry. When hydrogen is produced with a low carbon footprint, it can play seven major roles in the energy transformation.*" In every area, hydrogen can play an important role of decarbonisation as Figure 7 describes (Hydrogen Council, 2017: 5).

1) the role of hydrogen to enable a large-scale, efficient renewable energy integration,
2) the role of hydrogen to distribute energy across the sectors and regions,
3) the role of hydrogen to act as a buffer to increase the system resilience,
4) the role of hydrogen to decarbonise transport,
5) the role of hydrogen to decarbonise the industry energy use,
6) the role of hydrogen to serve as a feedstock using the capture carbon,
7) the role of hydrogen to decarbonise the heating of buildings.

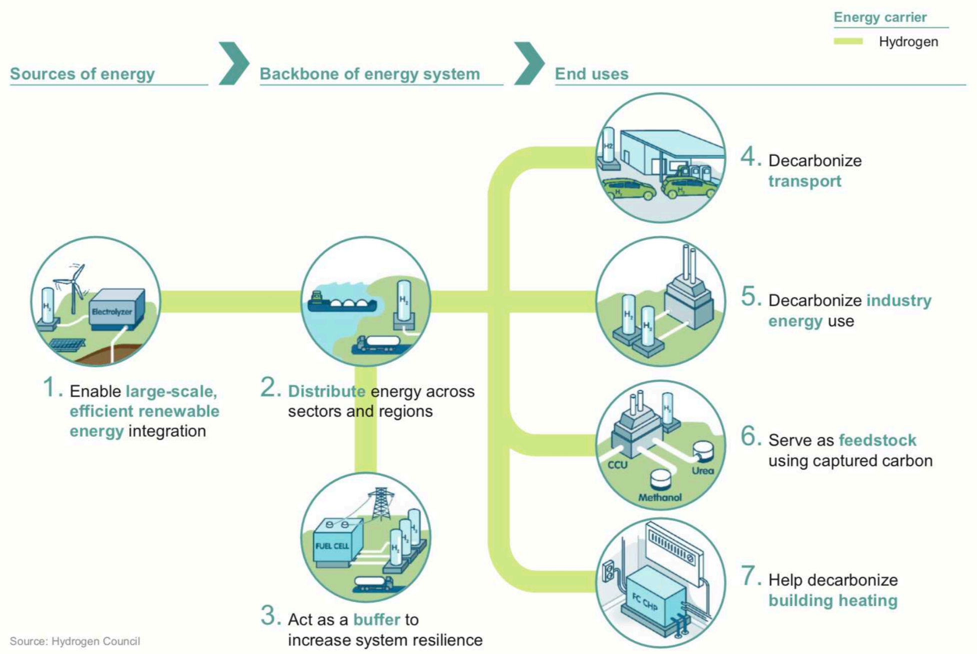

Figure 7: The Seven Roles of Hydrogen in Decarbonizing the Major Sectors of Economy. Source: (Hydrogen Council 2017: 5)

The transformation towards a low-carbon economy will need a change through the entire energy system, involving the large-scale investments. The expecting challenges aim at the five following areas and hydrogen is abundant in ability successfully overcoming all of them:

1) balancing of power supply and demand,
2) transformation of energy infrastructure,
3) decarbonisation of global buffer capacities,
4) decarbonisation of hardly electrifying end-use application,
5) carbon capture and storage or use.

Next chapters analyse 5 challenges and roles of hydrogen in the process of energy transition towards a cleaner, more sustainable energy system.

4.4 The Balancing of Power Supply and Demand

The raising capacities of the more intermittent renewable power energy could destabilise the balance between the supply and demand. The power generation from the variable renewable energy sources often pushes the power system to its limits. The list of some of the above-mentioned challenges is as follows:

- the grid capacity,
- the intermittency,
- the back-up generation capacity,
- the low-carbon seasonal storage.

It is difficult to match the variable electricity supply and demand throughout the day or between the seasons of the year. As the share of the renewable electricity in the electricity mix grows to 40% in 2040, it will emphasize the need for the operational flexibility. The increasing electrification along with the limited electricity storage capacity, will require some new solutions to secure the operational flexibility. There are several possibilities to achieve the flexibility. One of them is an upgrade of the grid infrastructure, another one is a short or a longer-term supply and demand side balancing. The balancing is usually provided by the flexible back-up power generation, as well as by the demand-side management, or the energy storage facilities.

The Role of Hydrogen to Enable the Large-scale, Efficient Renewable Energy Integration

Hydrogen as a versatile energy carrier can offer some valuable advantages, as it avoids CO_2 and all the emissions, such as the particle matters and the SO_x and NO_x emissions. It can be deployed at a large scale and can be available everywhere.

There are two ways in which hydrogen improves the efficiency and flexibility of the energy system: a valorisation of the excess electricity and a long-term carbon-free seasonal storage, that can be seen in the Figure 8. The graph shows the simulation for Germany in 2050. The oversupply generated by the renewables during the summer months can be transferred by the electrolysers and seasonally stored in the hydrogen carriers. Then it can be used during the periods of deficits, usually in winter when the load demand is higher than in summer.

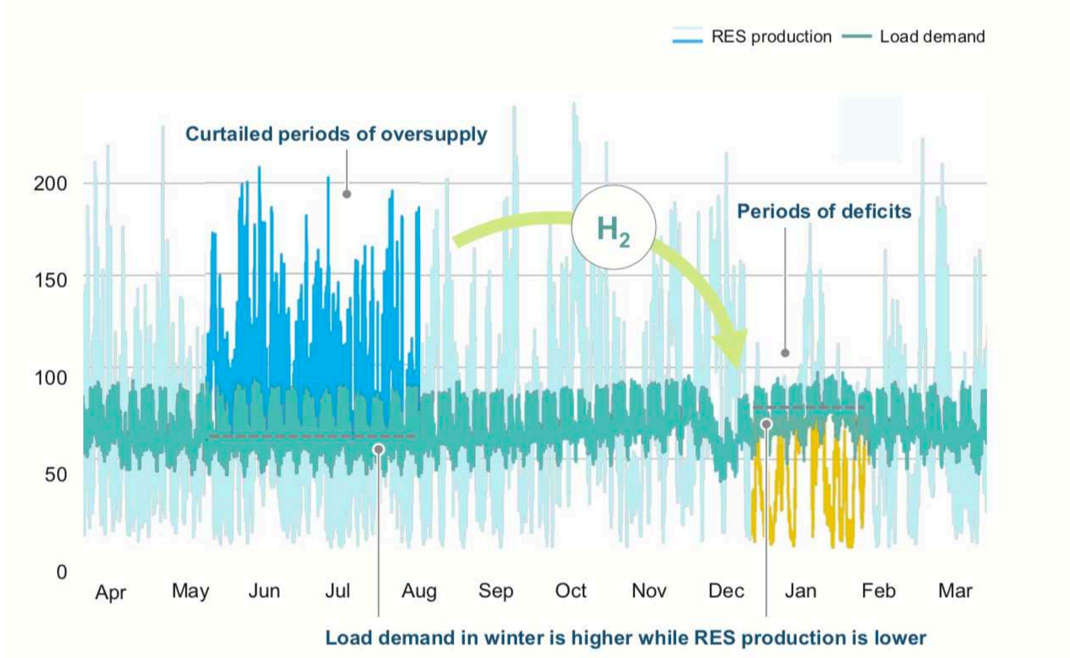

Figure 8: The Electricity Supply and Demand – the Simulation for Germany 2050 (in GW). Source: (Hydrogen Council 2017: 6)

The Excess Electricity Valorisation via the Electrolyser

As a result of significant growth of the renewables, the electricity grid goes sometimes out of the capacity due to the peak power generation periods. This situation occurs more frequently at nodes with a high share of renewable power generators. Therefore, the renewable electricity production is often curtailed. However, using the hydrogen as a storage of the converted renewable electricity, especially the curtailed one, is going to be a big challenge soon. The electrolysis can convert the excess electricity into hydrogen during the surplus periods. Vice versa, hydrogen can then be reused to provide the back-up power during the power demand or can be used directly in other sectors such as transport, residential heating and cooling, or industry (Hydrogen Council, 2017: 5). Hydrogen with a low-carbon footprint has the chance to contribute to the significant reductions in the energy-related CO_2 emissions. Thus, the use of the renewable resources for the hydrogen generation is very attractive from the environmental point of view.

The potential of valorisation of the curtailed renewable electricity is significant. For example, Germany is planning to achieve a substantial portion of the renewable energy after 2030. The Fraunhofer Institute for Solar Energy Systems, when estimating the storage, required to achieve 100% renewable energy in Germany by 2050, and concluded that this storage would consist of 24 GWh of the stationary battery applications, 60 GWh of the pumped hydro, 33 GW of the electrolysers and 670 GWh of the heat storage (Palzer & Henning, 2014: 13–28).

The advantages of the hydrogen electrolysers for the better integration and deployment of the renewables are as follows:

- They offer the centralized or decentralized source of the primary or backup power.
- They enhance the grid flexibility. The power from hydrogen can be switched on and off quickly. Thus, hydrogen can help to settle the sudden drops in the renewable energy supply, especially in the conditions of changeable weather.
- They provide some ancillary services to the grid, such as the frequency regulation.

Hydrogen can also be used in the hydrogen fuel cell combined heat and power units (CHPs) in industry and buildings, that allows to link the heat and power generation. Moreover, hydrogen markedly enhances the efficiency of the generated electricity and heat and improves the flexibility of the whole energy system (Hydrogen Council, 2017: 11). Its potential is discussed in the following chapters.

Hydrogen can Serve as a Long-term Carbon-free Seasonal Storage Medium

While the batteries, super-capacitors, and the compressed air are more suitable for the balancing, using hydrogen for long-term carbon-free seasonal storage represents the optimal solution in the future. Hydrogen can compete the above mentioned due to its much higher storage capacity and the storage timespan needed to cover the seasonal imbalances, as Figure 9 clearly shows (OECD/IEA, 2015: 20). The pumped hydro offers an alternative to hydrogen for the large-scale long-term energy storage. The pump hydro segment currently accounts for more than 97% of the global power storage with the installed power of 153 GW worldwide (International Hydropower Association, 2018). However, its residual untapped potential is subject to the specific local geographic conditions and bounded to about 1% of the annual global power demand 25570 TWh in 2017 (IEA, 2018: 11). This is not enough to satisfy the seasonal demand differences. For example, in Germany the energy demand used to be about 30% higher in winter than in summer, while the renewable generation is typically 50% lower in winter than in summer, as Figure 8 shows.

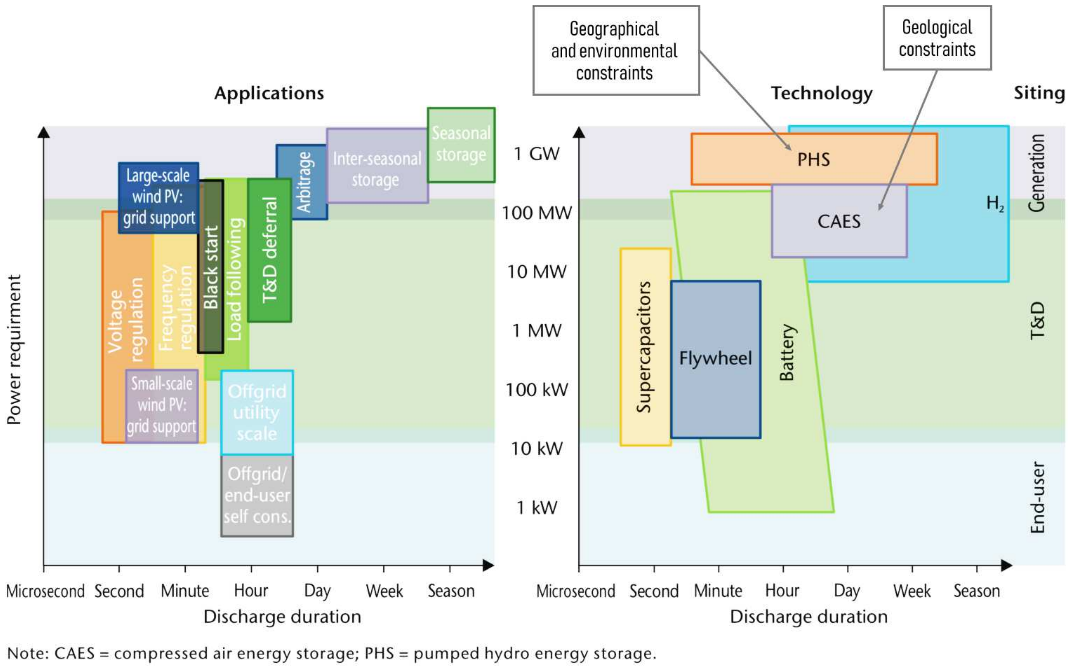

Figure 9: The Technology Overview of the Carbon-free Energy Storage Technologies. Source: (OECD/IEA 2015: 20)

Nowadays, hydrogen remains as a pioneer among the energy storages, however, a couple of hydrogen storage demonstration projects is being planned, announced, or launched around the world – e.g., in Canada, Japan, the Asia-Pacific region and in Denmark in EU. Furthermore, the underground storages in the depleted oil and gas fields, or in even more suitable salt caverns, can store large volumes of hydrogen. This sector of industry is well-established without any major technological barriers. Together with the RES share growing, the deployment of the hydrogen long-term storage solution is awaiting to accelerate. In 2030, the cost of the hydrogen storage system is projected to drop down to 140 €/MWh (power to power) for hydrogen stored in salt caverns. This is even less than the projected cost for the pumped hydro storage (about €400/ MWh in 2030). On the other hand, the total round-trip efficiencies of the hydrogen-based energy storage is low. The 2015 technology status indicates only a 29%-efficiency, as the Figure 10 demonstrates. However, the massive development and the economy of scale increase the efficiency continuously and the estimate for 2050 rises to 40%. The large pumped hydro plants usually achieve more than a 80%-round-trip efficiency. The mass deployment is not expected due to both the geographical and environmental constrains.

Figure 10: The Roundtrip Efficiency - the Power-to-power H2 Application (in %). Source: (OECD/IEA, 2015: 21)

In Germany the unused potential of the seasonal hydrogen storage in caverns is about 37 billion cubic meters. This would be sufficient to store 110 TWh of hydrogen, covering the projected full seasonal storage need. Hydrogen can balance the energy system more economically by the easier integration of the large amounts of the intermittent energy sources in the system and provides the much-needed flexibility to maintain the resilience of the system. (Hydrogen Council, 2017: 7)

4.5 The Transformation of the Energy Infrastructure

To ensure the security of supply, the energy infrastructure will require the major transformation on the global, as well as the local level. Currently, on the global level about 30% of the global primary energy supply is merchandised across the borders, covering a mixture of the energy carriers such as oil, gas, coal and electricity. Except for the storages, an open cross-border energy infrastructure will be important for ensuring a secured energy supply, unequally located across the world's regions. On the level of the regions or cities within a country, a new mixture of the centralized and decentralized energy supply will rise. Such a pending oversupply will emphasise the importance of the energy infrastructure adjustment (Hydrogen Council, 2017: 2).

The Role of Hydrogen in the Energy Distribution across the Sectors and Regions

In the future, the power system will require an alternative distribution of the renewable energy for several reasons. Some countries, such as Slovakia, do not have an advantageous position to generate energy using solely the wind or solar power. Other countries, such as Germany, have some regional disbalances in the power production and power consumption. While the north Germany often generates a surplus of electricity from wind, Bavaria suffers from a lack of the renewable electricity. The long-distance transport of electricity usually causes energy losses. The pipeline transport of hydrogen reaches almost 100% efficiency. Building of the new transmission power lines across the densely populated areas is very expensive and sometimes even impossible. Therefore, the transformed power to hydrogen can be injected to the existing natural gas grid to transport and store a huge amount of energy in a cheaper way. This benefit makes hydrogen an economically attractive option mainly by transporting the renewable energy at a large scale and over large distances. As hydrogen has a high energy density and is easily transported, it can help distribute energy effectively and flexibly.

The hydrogen distribution might serve as a long-term strategy, aimed at the handling the continual growth of the new RES, or ensuring an adequate energy supply in the winter, when the renewable energy sources produce less electricity.

Hydrogen offers some valuable advantages in this context, as it avoids CO_2 and the particles emission, it can be deployed at a large scale, and can be made available everywhere. There are two ways in which hydrogen improves the efficiency and flexibility of the energy system. Hydrogen can allow the transition to the cost-effective and clean energy infrastructure, contributing to the safety of energy supply both on local and national levels. Hydrogen distributed by ships, pipe, or by the liquefied tube trailers can carry energy effectively throughout the cities and regions. Economy of scale can decrease the costs for liquefaction and transport by 30 to 40% in the next 15 years. The utilisation of the existing gas grids to distribute hydrogen has been tested, however it has not been applied at a large scale yet.

4.6 The Decarbonisation of Global Buffer Capacities

The energy system needs the buffers to ensure its smooth operation by maintaining a reserve in the amount of approximately 15% - 25% of the world's total annual energy demand. A buffer works like a shock-absorber in the car. In the energy system it absorbs the energy supply chain shocks, it provides some strategic reserves and anticipates the supply and demand imbalances. Nowadays, the fossil energy carriers provide most of the storage capacity. When the electrification increases, such reserves will no longer be sufficient to ensure the secure energy supply for all consumers. As the price of CO_2 is continuously rising, the representatives of the power sector think intensively about switching to the low-carb alternative energy carriers, and the use of fossil fuels as a backup source of energy might decrease.

The Role of Hydrogen to Act as a Buffer to Increase the Flexibility of the System

Regarding its storability and distribution flexibility, hydrogen is a sustainable and green option for overcoming the buffer challenge and ensuring a smooth operation of the energy system. The main commercial stakeholders, e.g. Air Liquide S.A., Royal

Dutch Shell, The Linde Group, as well as the other members of the Hydrogen Council, see no indication that the amount of the buffering demand could be reduced in the future. With the utmost certainty, the most efficient buffer would be a mixture of the energy carriers as fossil fuels, biofuels / biomass / synthetic fuels, and hydrogen that reflect the different requirements of the end-use applications.

4.7 Decarbonisation of the Hardly Electrifying End-use Applications

Some energy sectors and transport applications are inconvenient to electrify via the grid or with batteries. Concerning the heavy-duty vehicles, non-electrified trains, maritime transport, aviation, as well as some energy-intensive industries, a direct electrification is and probably will be technologically challenging or uneconomic, even at very high prices of CO_2. In other applications, such as light-duty vehicles, a direct electrification can be appropriate, but does not always fulfil the requirements concerning the range and the charging comfort. In these sectors, where some obstacles prevent a direct electrification, hydrogen can be a viable solution.

The Role of Hydrogen in the Transport Decarbonisation

For many decades the fossil fuels have dominated the fuel mixture satisfying the world's transport needs. Both gasoline and diesel report for 95% of the total fuel consumption and in 2016 23% of the global carbon emissions. The Fuel Cell Electric Vehicles (FCEV) play an important role in the decarbonization of transport. The emissions increased by 2.5% annually between 2010 and 2015 (OECD/IEA, 2017: 13).

The current enhancement of efficiency of the internal combustion engines (ICE) and a mass introduction of hybrid vehicles, such as the hybrid electric vehicles (HEV) and the Plug-in Hybrid Electric Vehicles (PHEV), are already reducing the vehicle emissions. Nevertheless, the fully decarbonized transport will require mass deployment of the zero-emission vehicles, such as the Battery Electric Vehicles (BEV) and the FCEVs, eventually the hybrid combinations thereof. It is expected that the advances in technology and the new trends in mobility, e.g., the autonomous driving technology and the shared mobility, will influence the relative levels of deployment and the transition speed. Both battery and fuel cell electric vehicle types will benefit from using the complementary technologies, however, they are aimed to serve different segments and customers. Besides the decreasing of the CO_2 emissions, both also significantly contribute to the local air quality improvement and noise reduction.

The following Figure 11 explains why the FCEVs offer several significant benefits. They can drive long distances without a need to be refuelled (e. g. Toyota Mirai already more than 500 km). This feature is highly valued by the consumers due to the quick refuelling taking from 3 to 5 minutes, like the current gasoline/diesel cars. Thus, the customers do not need to change their habits, which contributes to the consumer convenience. While the BEVs are more suitable for the short-distance trips, the FCEVs are better at dealing with long-distance range and heavy loads. The FCEVs will be especially important concerning the decarbonization of the passenger cars, e.g., the medium to large cars, fleets, taxis, and also heavy-duty transportation, buses, and non-electrified trains. The utilization of the synthetic fuels based on the green hydrogen concerning the shipping and aviation is also being explored.

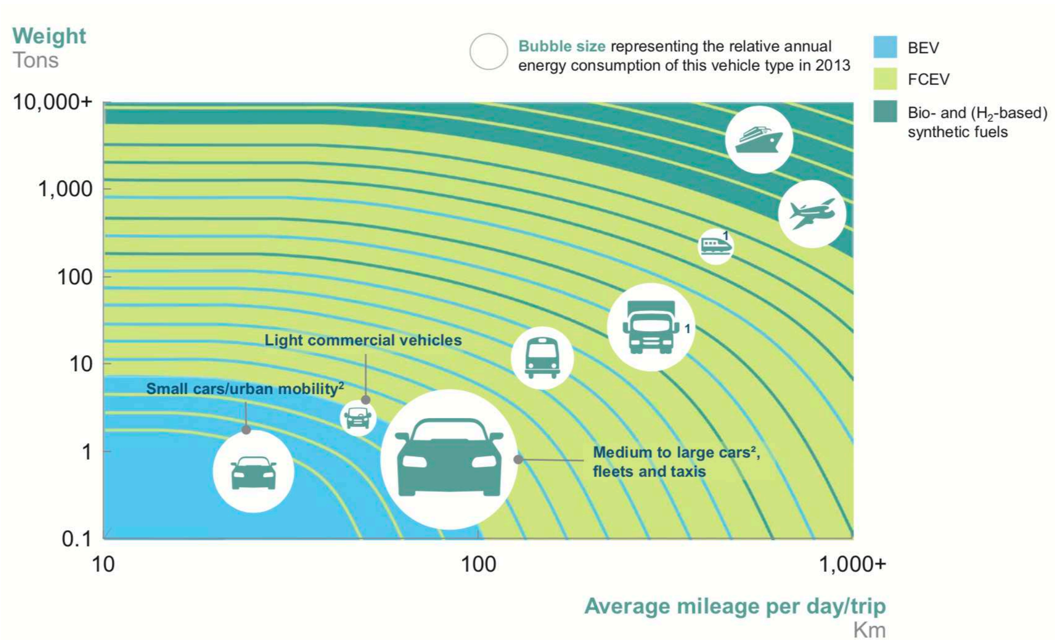

Figure 11: The role of FCEVs in Decarbonizing Transport. The Projected Economic Attractiveness. Source: (Hydrogen Council, 2018: 8)

Despite the infrastructure of the electric charging stations, the hydrogen refuelling stations can be built directly in the existing gasoline distribution and retail infrastructure, thus it would lower the costs and preserve the local jobs and capital assets. The integration of variable RES in power systems and the growing emissions from the transport sector could significantly accelerate the future deployment of hydrogen (Ajanovic & Haas, 2018: 285).

The Role of Hydrogen in the Industry Decarbonisation.

As well as in the transport sector, the fossil fuels provide the energy for the industrial processes that generated about 24% of the global emissions in 2014 (IEA, 2020).

An enormous potential still exists in the improvement of energy efficiency in the sector of the industry. The industry mainly needs to improve the waste heat recovery, thus, to reduce the need for energy. The recycled waste heat can be transformed into the valuable hydrogen. Both low and high-grade heat is used in the process of the industrial production. As the following figure describes, mainly coal and natural gas is broadly used referring the process heat above 500 °C today (Heat Roadmap Europe 4, 2017: 4).

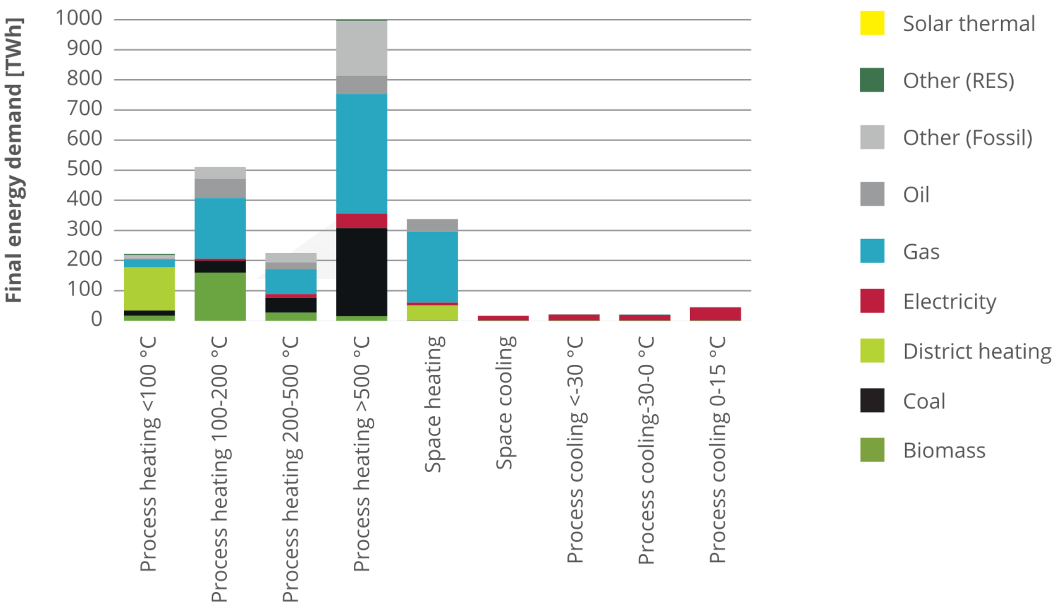

Figure 12: The Industry Process Heating Energy Carriers in EU28. Source: (Heat Roadmap Europe, 2017: 4)

Many options are offering to industry how to decarbonise low-grade heat. While heat pumps and electric resistance heating give advantages in certain geographic locations, hydrogen is obviously beneficial when it is available as a by-product of the chemical industry or when a specific industry needs heat and stable power supply that fuel cells can provide. Hydrogen combustion in burners or utilise in fuel cells can provide a zero-emission alternative for heating.

High-grade heat above 400°C is difficult to decarbonize, but hydrogen burners can complement electric heating to generate high-grade heat, depending on local conditions. Some regions might prefer industrial use of hydrogen technologies instead of electricity, due to technical constraints of their energy system.

The Role of Hydrogen in Decarbonisation of the Building Heating

Space heating and warm water supply account for about 80% of residential energy consumption worldwide. About 50 EJ of energy is used for residential heating, responsible for 12% of global emissions. In EU28 single-family houses use twice as much energy for space heating as multi-family houses, in both natural gas dominates as primary source of heating (Heat Roadmap Europe 4, 2017: 5). It can be seen in the Figure 13. Hydrogen can be one of the proper choices for decarbonizing building heating. Right choice strongly depends on local conditions.

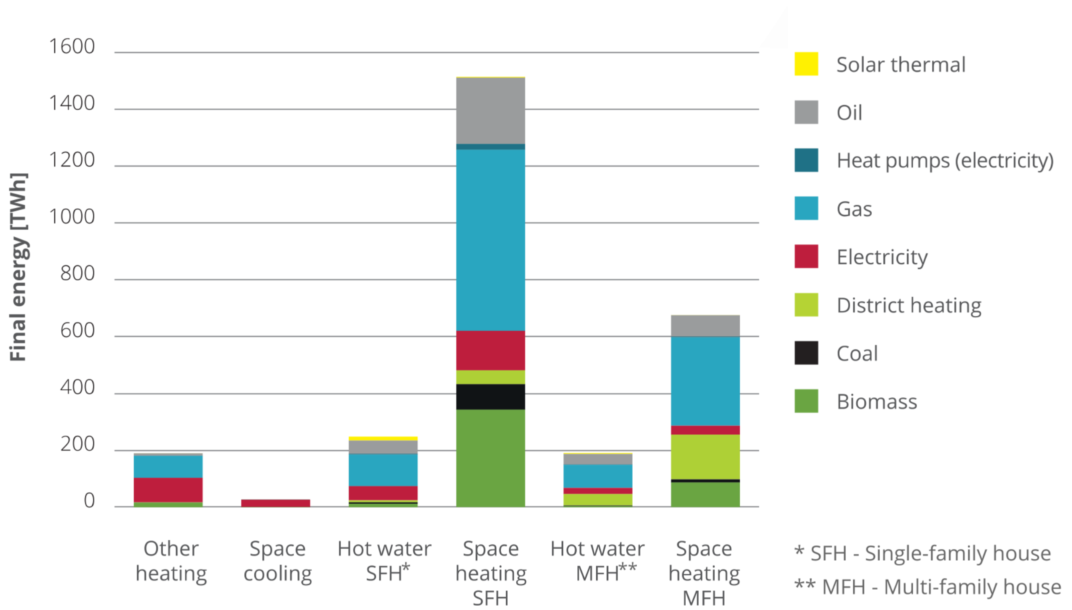

Figure 13: The Final Energy Consumption in the Residential Sector in EU28 in 2015. Source: (Heat Roadmap Europe 4, 2017: 5)

Building heating can use hydrogen directly as a fuel in boilers or using advanced hydrogen technologies, such as fuel cell micro CHPs, or ideally a combination of both. Fuel cell micro CHPs serve as energy converters. They can offer high efficiency for heat and power generation, totally > 90%. Hydrogen itself can be used as a fuel directly or blended with gas, what can allow partially decarbonizing the gas grid. With relatively small technical adjustments and investments, the existing gas grid can safely distribute a mixture of hydrogen and natural gas.

5 The Role of Hydrogen to Decarbonize Slovak Economy

Following the Paris Declaration to which the Slovak Republic subscribed, hydrogen could become one of the main tools for transforming the economy into a low-carbon economy. The Slovak Government has recently been prioritised the use of hydrogen to achieve carbon neutrality by 2050. Hydrogen could become one of the main tools for transforming into a low-carbon economy in Slovakia.

Industry

Slovakia has the potential to decarbonise refinery, chemical and steel industry by green hydrogen replacing currently used fossil-based hydrogen. There are currently two large industrial hydrogen prosumers in Slovakia. Slovnaft and Duslo both produce and immediately consume fossil-based hydrogen, known as grey hydrogen. Steam Methane Reforming is a cost-effective but carbon-intensive way of hydrogen production where every kilogram of hydrogen emits nine kilograms CO_2.

Duslo, the member of the Agrofert group, operates an ammonia plant and produces fertilisers as the final product. Slovnaft, the member of the MOL Group, operates a refinery, producing fuels and plastics. Steelmaker USS Košice intends to replace part of a blast furnace iron production to a direct reduction of iron. Duslo, the largest ammonia plant in Central Europe with daily production of 1600 t ammonia use more than 280 t grey hydrogen daily. Duslo became the fourth most intensive industrial CO_2 emitter in Slovakia in 2019 with 0,985 thousand tons CO_{2eq}. The first position held a steelmaker USS Košice with 5 million tons CO_{2eq} (European Commission, 2020). From the medium-term horizon, the steelmaking industry has a tremendous potential to become greener using a direct iron reduction process via electricity with hydrogen rather than use the blast furnace route.

Heating

Slovakia has the second densest gas grid within the EU. It gives a significant potential to distribute, store and use hydrogen effectively mainly in the heating sector. Almost 70% of natural gas consumes heating and cooling sector in Slovakia. It represents absolutely the highest share within the EU countries Figure 14. Slovakia belongs among the countries with seasonal gas-based consumption, giving a chance to store seasonal energy surplus from PV plants in the seasonal hydrogen geological storage and use summer energy during winter heating seasons. Carbon-zero hydrogen heating can significantly improve air quality in urban agglomerations as well as in the rural valleys. Hydrogen will be injected into the pipes in larger volumes when the price of hydrogen approach to the natural gas price. This situation will happen when fossil fuels will be encumbered by CO_2 tax, and hydrogen cost will drop down due to scaling up the hydrogen technologies. Thus, a total gas grid volume can serve as a cost-effective hydrogen energy storage and distribution highway after 2030.

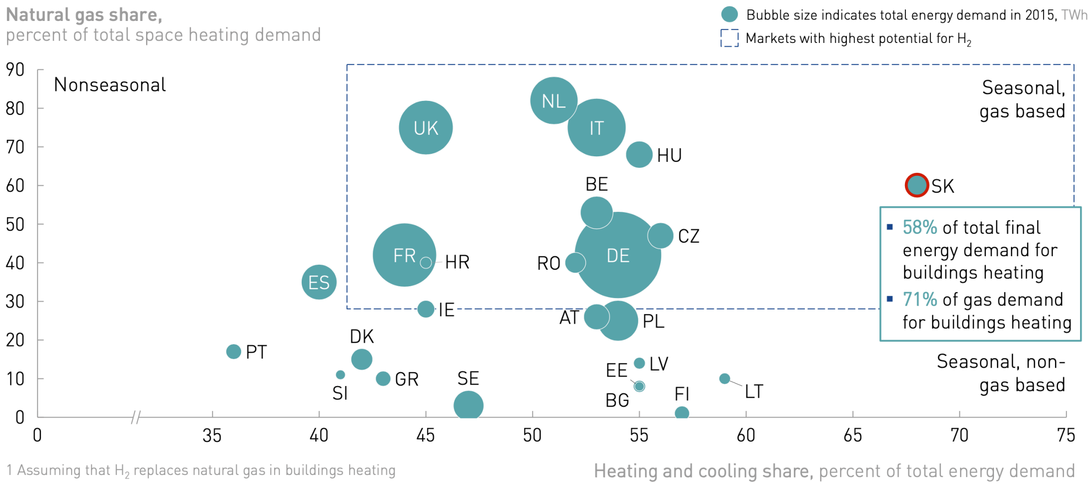

Figure 14: The Priority Countries for Hydrogen Adoption within the EU. Source: (FCH 2 JU, 2019: 36).

Transport

Four automotive production sites, such as Volkswagen, PSA, Jaguar-Landrover and Kia, need to transform their production pipelines to the low-carbon path. Especially, Kia Motors already produce a fuel cell electric powertrain in South Korea. Kia Motors Slovakia operates the unique plant in Teplička nad Váhom in Slovakia, the only plant manufacturing engines for Kia and Hyundai in Europe. Thus, a possible transition from internal combustion engines to fuel cell powertrain production will have a significant positive impact not only for Kia Motors itself but for all the local component contractors too.

The city bus and passenger rail operators are interested in zero-emission vehicles. A pilot project of two regional hydrogen trains is developing today to decarbonise the first part of 57% so far not electrified railways in Slovakia (Railways of the Slovak Republic, 2020: 15, 16). A considerable potential has decarbonisation of heavy-duty transport by hydrogen. Slovak Hydrogen Association estimates the hydrogen transport deployment for 2030 as shows Figure 15. The calculation has been made based on average of the French, German and Korean targets and adjusted by share of GDP and population of Slovakia. Delay in the deployment of vehicles due to the lack of infrastructure is considered too.

When an Important Project of Common European Interest (IPCEI), Black Horse, succeeds, 10000 heavy-duty hydrogen trucks will replace diesel ones in V4 countries (Hydrogen Europe, 2019). Compare to more than 500000 registered trucks in V4 countries, 10000 hydrogen trucks seem to be a negligible, but enough for hydrogen trucks automakers such as Daimler, Iveco or Nikola to run a large-scale production and reduce capital costs of hydrogen trucks. The total number of fuel cell trucks can rise to 1500 in 2030 in Slovakia representing only 2% from all the registered diesel trucks in Slovakia in 2020 as is shown in Table 3.

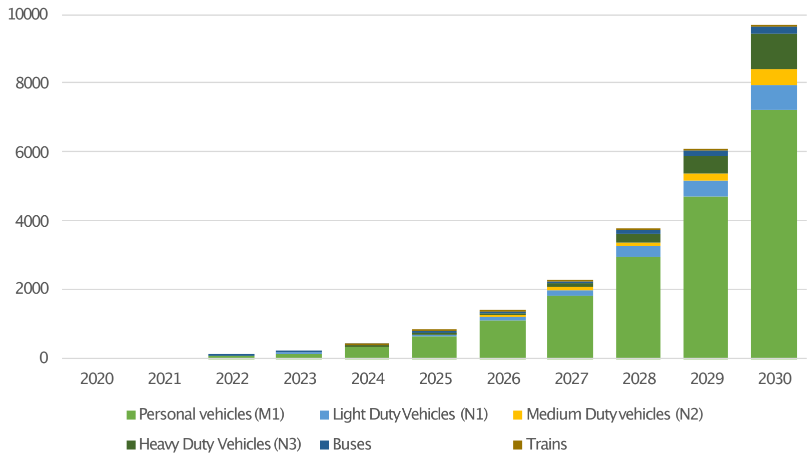

Figure 15: The Estimation of the Development of Fuel Cell Vehicles in Slovakia. Source: (Slovak Hydrogen Association, 2020, unpublished)

The total share of FCEVs in 2030 on the Slovak roads and rails will strongly depend on many factors, mainly on vehicle price and hydrogen infrastructure availability. Without massive state support to build hydrogen infrastructure and bonuses in the purchase of FCEVs, the overall share on all the registered vehicles will stay negligible as a Table 3 explains.

Table 3: The Estimation of the FCEV Share in 2030. Derived from: (Internal calculation of Slovak National Hydrogen Association, 2020, unpublished)

Vehicle category	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Aug-20	Share**
Personal vehicles (M1)	0	0	65	154	326	644	1 105	1 831	2 960	4 695	7 209	2 426 881	0,30%
Light Duty Vehicles (N1)	0	0	0	15	33	64	110	183	296	469	721	242 860	0,30%
Medium Duty Vehicles (N2)	0	0	0	0	10	20	30	60	120	240	500	24 011	2,08%
Heavy Duty Vehicles (N3)	0	0	0	0	20	40	60	120	240	480	1 000	49 119	2,04%
Buses	0	0	5	10	20	30	45	70	100	140	200	7 397	2,70%
Trains	0	0	0	0	2	2	6	6	10	20	40		
Total	**0**	**0**	**70**	**180**	**410**	**801**	**1 356**	**2 270**	**3 726**	**6 044**	**9 670**		

The Domestic Hydrogen Demand

Today, industry sector produces and consumes at least 200 thousand tons of fossil-based hydrogen annually. Changing a part of an iron making process from a carbon furnace route to an electric-hydrogen process, additional 25 to 50 thousand tons of hydrogen annually can be produced with a low carbon emission footprint after 2030. The transport sector will need twelve thousand tons of green hydrogen under the assumption that the hydrogen transport topic remains the priority of the Slovak government. In this case, 9760 vehicles fuel cell electric vehicles cars can be deployed on the road till 2030. If Slovakia decided to replace all the grey hydrogen consumed in the industry sector today, then 10 TWh of additional renewable electricity is required annually as Table 4 presents. The table shows the primary consumers of hydrogen in Slovakia. It describes annual H_2 consumption, from when the consumption is awaiting, the trend of consumption and then the necessity of renewable power for water electrolyses to meet the clean hydrogen demand.

Table 4: The Renewables Necessary for the Clean Hydrogen Production in Slovakia (own calculation based on discussion with industry representatives and NVAS, 2020)

Consumer	H2 consumption (tons)	Fom the year	Trend in H2 consumption	Power consumption (TWh)	Installed power needed		
					Wind 70% (GW)	PV 30% (GW)	Mix (GW)
Slovnaft (refinery)	100 000	2 020	stabil	5,0	1,14	1,22	2,36
Duslo (ammonia)	100 000	2 020	stabil	5,0	1,14	1,22	2,36
USS Košice* (steel)	50 000	2 035	growing	2,5	0,57	0,61	1,18
Transport sector*	12 000	2 030	growing	0,6	0,14	0,15	0,28
Total	**262 000**			**13,1**	**2,99**	**3,20**	**6,19**

* estimation

Assumptions: Electrolyser efficiency (LHV) 68%, need of 50 kwh/kg H2 produced, Wind capacity factor 35%, PV capacity factor 14%

Grey hydrogen is fossil-based hydrogen-producing via steam methane reforming of natural gas. This hydrogen serves as a feedstock for industry. Every ton of grey hydrogen refers to 9 tons of released CO_2 in the air. Electrolysis can save 1,8 Mt CO_2 annually. When 50 kWh of green power can produce via water electrolysis 1 kg of clean hydrogen, and a capacity factor of the future wind farms in the best Slovak sites is 35%, then annual demand for renewable hydrogen meet 262 thousand tons in a long-term horizon. If the Wind and PV installing power will set in ratio 7:3, then rated capacity 3 GW wind and 3,2 GW of PV will meet all the demand. When a new type low-wind 6,2 MW wind turbines cover such a demand, 482 wind turbines can meet the requirement. If 1 MW of PV plant takes approximately 1,2 ha area, then about 3840 ha (area 6,2 x 6,2 km) will cover the PV plants. Power generation and consumption remain stable for the last three years in Slovakia, but the replacement of grey hydrogen with renewable hydrogen requires extra one-third electricity generation in Slovakia. In this case, the consumption is more than four times greater than the Slovak NECP estimates until 2030 (Ministry of Economy of the Slovak Republic, 2019a). Thus, steelmaking and clean transport will drive the rapid growth of RES after 2030.

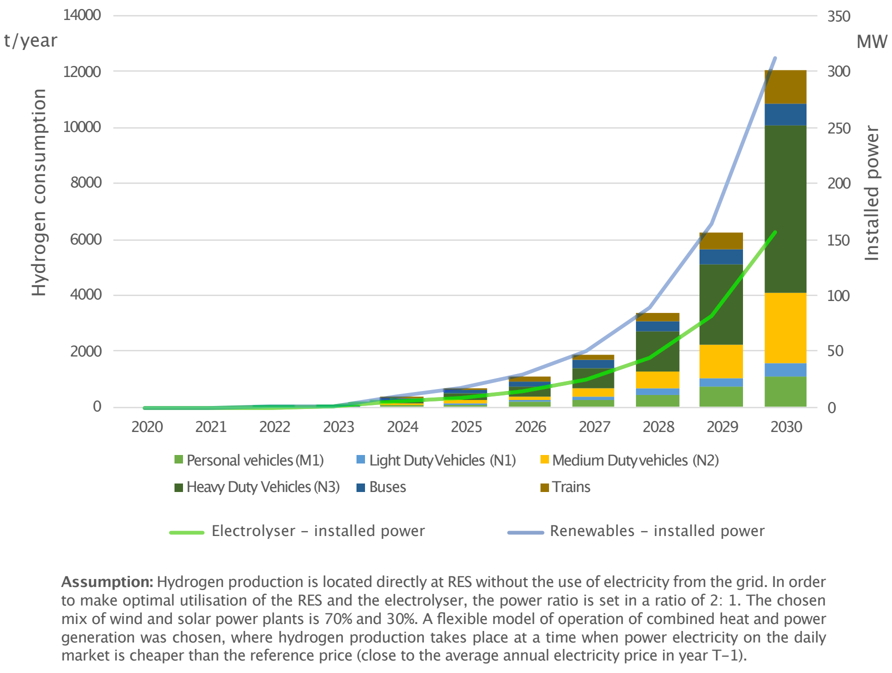

Figure 16: The Estimation of the Annual Hydrogen Consumption Development and the Needful Installed Power of the Electrolysers and Renewables. Source: (NVAS, 2020, unpublished)

A successful carbon-neutral transition until 2050 needs to develop a long-term trajectory not only for clean hydrogen production but for all the hydrogen value chain.

Industrial demand after green hydrogen produced by water electrolysis will consume 10 TWh of renewable electricity annually under the condition of 66-68% efficiency in 2030 (IEA, 2019: 44, 45). The total installed power of renewable sources in Slovakia was 2,5 GW in 2018, excluding large hydropower plants with installed power of 1 GW (Ministry of Economy of the Slovak Republic, 2019b: 3). Plan for 2030 is 3,1 GW, resp. 1,6 GW, that means a nominal power growth of 0,6 GW in PV and wind installations. According to the Slovak NECP, the growth of renewable power generation from 2,7 to 4,2 TWh in 2030 is focused on variable renewables. Therefore, variable renewables would generate by 1,5 TWh of renewable power more in 2030 than in 2018. So, Power-to-Hydrogen plant should consume 0,6TWh in 2030 without significant problems (Ministry of Economy of the Slovak Republic, 2019a: 44–47). As Figure 17 shows, if Slovakia wants to replace all the grey hydrogen in 2030, then the government will have to revise NECP and add additional RES capacity that will generate additional 9,5 GW annually.

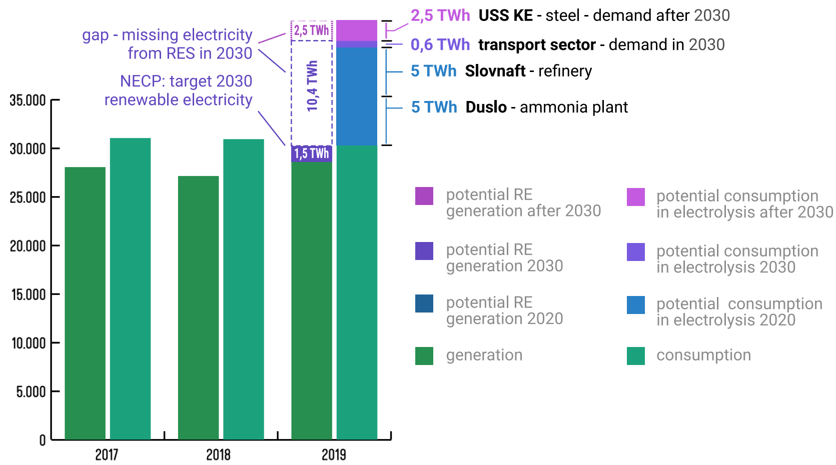

Figure 17: The Electricity Generation and Consumption in Slovakia (GWh), the Potential of the Clean Hydrogen Production. Own chart based on (Regulatory Office for Network Industries, 2020: 51)

6 The Case Study: a 150 MW Power-to-Hydrogen Plant

The case study refers to the strategic objective of the European Commission of deploying the large electrolysers in Europe. The objective is to install an operates a 150 MW variable renewable energy source, specifically wind farm supplying a 50 MW PEM electrolyser via direct connection producing clean hydrogen for ammonia plant and the nascent hydrogen mobility in Slovakia. Wind farm together with PEM EC creates Power-to-Hydrogen plant. The plant is not a single purpose plant, delivering all its power from wind farm to the electrolyser, but the plant, distributing power to the electrolyser according to selected electricity supply-demand scenario.

Moreover, the Power-to-Hydrogen plant can profit from additional benefits, such as revenues from ancillary services for TSO, or waste heat and oxygen sale. Variable RES also can profit from a fixed level of the electricity purchase price for EC. The Power-to-Hydrogen plant project is situated in the south-west of Slovakia near Duslo ammonia plant. This location fulfils all the conditions for Power-to-Hydrogen plant site: flat and windy farmland, existing transformation station with direct access to the high capacity transmission grid, tap water and industrial customer for green hydrogen that can consume all the hydrogen at a competitive price.

6.1 The Technology Overview

The Power-to-Hydrogen system consists of a wind farm, a renewable electricity source, and a PEM electrolyser, as a block diagram in Figure 18 shows. For this case study a 150 MW wind farm has been preferred due to its lowest levelised costs of electricity (ca € 45/MWh compared to € 70/MWh concerning a PV), and about twice as much full load hours annually compared to a PV plant in the conditions of Slovakia. In the Power-to-Hydrogen plant, the RES supplies electricity directly to the PEM electrolyser via the dedicated invertors and infrastructure. The electrolyser will be placed nearby a transformer station and connected to a very high voltage transmission grid in order to enable it to provide the ancillary services for TSO. Besides the power consumed for the regulation, no grid power is used for the production of hydrogen, except for the renewable power from the onsite RES. RES delivers electricity preferentially to the EC and the excess electricity to the grid. The clean hydrogen flows under the pressure of 30 bar to a near ammonia plant via a short, ca 1 km long pipe. Part of the hydrogen volume is compressed and filled to the tanks under the pressure of 200-300 bar before it is refilled to the cistern trucks and distributed to a hydrogen refuelling station in the range of 100 km. Hydrogen in the transport sector can be sold for a better price compared to the industry. Duslo can produce hydrogen from natural gas for the price in the amount of 1,2 €/kg. When the hydrogen mobility grows in Slovakia, probably most of the hydrogen will be consumed in the transport sector.

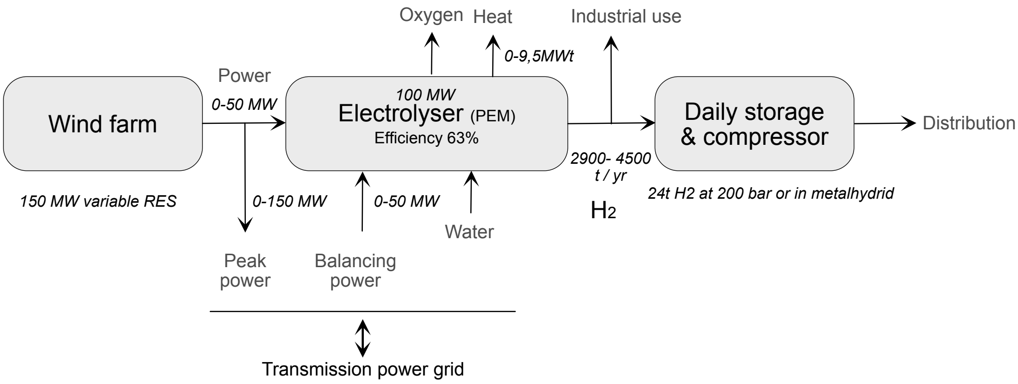

Figure 18: The Block Diagram of Power-to-Hydrogen Plant (own diagram)

The waste heat from the electrolyser, approximately half of the heat produced, can be captured and used for heating the greenhouses, while the electrolyser is situated far from the urban areas. Greenhouses need heat during the heating season. Therefore, the summer usage of the heat for tourism can be attractive from a regional point of view.

6.2 The Overpowering Strategy

The important objective is to find an optimal RES nominal power and the EC nominal power share in order to reach as high capacity factor in EC as possible. The higher EC utilisation leads to the lower Levelised Costs of Hydrogen (LCOH). A wind farm can supply the EC with a higher capacity factor than a same sized PV plant. On the other hand, a wind farm usually has a more extended period with the minimal renewable electricity production compared to the regular daily power supply from a PV plant. The combination of both types of RES could improve the optimising of the green power supply to the EC. However, it is out of the scope of the master thesis. This master thesis deals with a wind farm, as the only source of the renewable electricity, in order to achieve a more transparent business case simulation. One of the often-applied methods of how to increase the capacity factor of the EC is the **RES overpowering compared to the EC nominal power**. In this case, the wind farm nominal power is overpowered by factor 3 compared to the EC. In other words, the ratio of the EC's nominal power to the RES's is 1/3. In the absolute numbers it is 50 MW concerning the EC and 150 MW concerning the wind farm. As Table 5 shows, the overpowering increases the utilisation of the electrolyser on average by 60%. The row “RES=EC” in the table reflects the capacity ratio 1/1 (50 MW RES and 50 MW

EC) and the row “RES=3xEC” means a triple overpowering of RES to EC (150 MW RES and 50 MW EC).

Table 5: The Electrolyser Utilisation Growth by the RES Overpowering (own calculation)

Scenario	H2 off-peak		H2 flexi		H2 max	
FLH/CF	FLH	CF	FLH	CF	FLH	CF
RES=EC	1978	23%	2185	25%	3029	35%
RES=3xEC	3182	36%	3513	40%	4831	55%
Growth by	61%		61%		59%	

6.3 The Supply-demand Scenarios

The case study examines the RES and the EC supply-demand relationship within the Power-to-Hydrogen plant in 3 scenarios. All scenarios count with a triple RES overpowering compared to the electrolyser’s nominal power. Figure 19 illustrates an example of a daily renewable electricity generation in each scenario on a day with the average speed of wind. It also shows the supply way from RES to EC, eventually to the grid. In the first scenario, **H2 off-peak**, the electrolyser uses only the off-peak electricity, when the demand for electricity in the country is relatively low. It means during the working days it works at nights from 8 pm to 8 am, and at the weekends and on holidays it works for 24 hours. In the second scenario, the **H2 flexi**, the electrolyser uses the electricity like H2 off-peak and also when a spot market price drops under the level of the agreed EC price. In the third scenario, **H2 max**, the electrolyser uses the electricity from RES primarily without any limits, 24 hours a day annually. The charts also include the spot market price curve and the level of EC price - the purchase price of EC, for this case € 40/MWh. The value of € 40/MWh has been set as the optimal balance between the profitable operation of the wind farm and the acceptable electricity costs for EC. The price has been set close to the annual off-peak price and calculated based on the real data from 2019 derived from the Power Exchange Central Europe (PXE). The off-peak price for November 2020 was € 37,11/MWh and for 2021 it will be € 41,26/MWh. If the EC price will be set under the off-peak price, then the RES operator would lose any motivation to supply EC. Thus, a long-term contract between the RES and EC operators would be recommended. RES sales the excess electricity to the grid in every scenario. A contracting power trader will purchase the electricity for the future peak-load and the off-peak prices. This way the optimal and regular operation of the plant guarantees the low electricity costs for EC and the peak sale of electricity for RES.

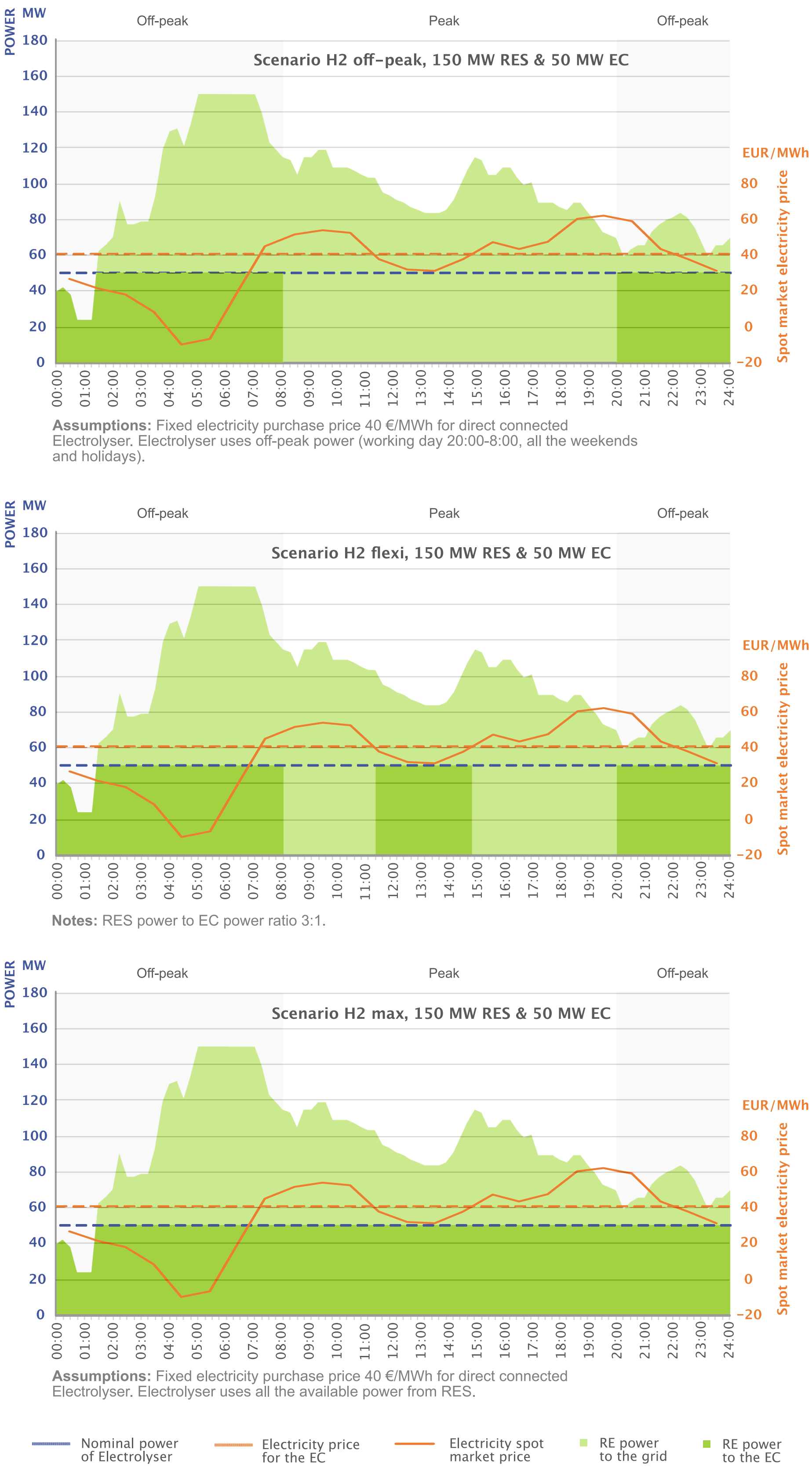

Figure 19: The Example of a Daily Diagram of the Renewable Power Distribution within the 3 Different Scenarios (own chart)

The H2 off-peak and H2 flexi scenarios support the resilience of the power grid by supplying the valuable peak power when the demand in the country is usually high. The advantage of the overpowering strategy shows the comparison in the example of the H2 flexi scenario in Figure 20, where RES to EC power ratio is 1:1. The chart below clearly shows that the utilisation of EC is reduced.

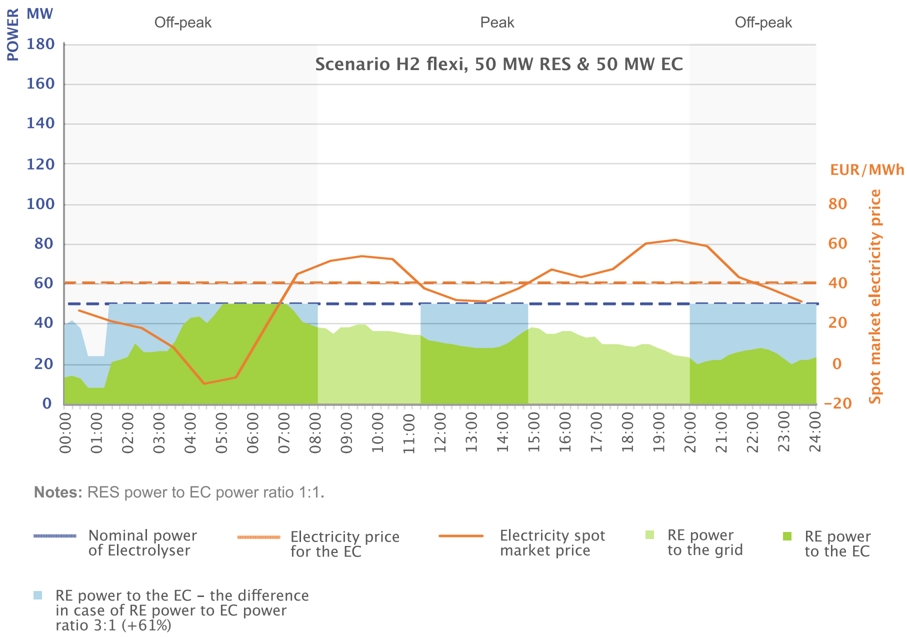

Figure 20: The Example of a Daily Diagram of the Renewable Power Distribution within the H2 Flexi Scenario in Case of RES to EC Power Ratio 1:1 (own chart)

6.4 Renewables

The installation of a large-scale variable RES, such as the wind or the solar one, require the appropriate wind and sun conditions, morphological conditions, areas without environmental, agricultural, or airspace zones. However, in practice they mainly need the social and political acceptance in Slovakia.

The International Renewable Energy Agency (IRENA) have recently published a cost analysis of renewables, where it is mentioned that the installation of the new renewables increasingly costs less than the cheapest fossil fuels. Solar and wind power costs have continued to fall, complementing the more mature bioenergy, geothermal and hydropower technologies. Solar photovoltaics (PV) show the sharpest cost decline over 2010-2019 at 82%, followed by concentrating solar power at 47%, onshore wind at 40% and offshore wind at 29%. (IRENA, 2020: 11, 12).

The Technical Appraisal

Nowadays, the range of power rate of a single wind turbine moves from 2-4 MW to 5-6 MW. For the Slovak wind conditions, the low-mid wind turbines class IEC S are suitable. The manufacturers design their onshore wind turbines for the specific wind conditions. The IEC S class turbines are designed for the locations with the average speed of wind up to 7,5 m/s. These turbines typically have the extra-large rotors to allow them to capture as much energy from the lower wind speeds as possible. For the purposes of this case study, the Siemens Gamesa 170 6,2 MW at 135 m hub height has been chosen. This brand-new low-wind turbine can also be placed on a 115- and a 165-m tower. Each turbine can generate 20,77 GWh of the clean electricity annually at the average annual wind speed of 6,5 m/s 135 m above the ground (DTU Wind Energy, 2020). Such a mean wind speed is available in the regions around the cities Nitra and Trnava to the south to the Hungarian border, as the wind map in the Figure 21 illustrates.

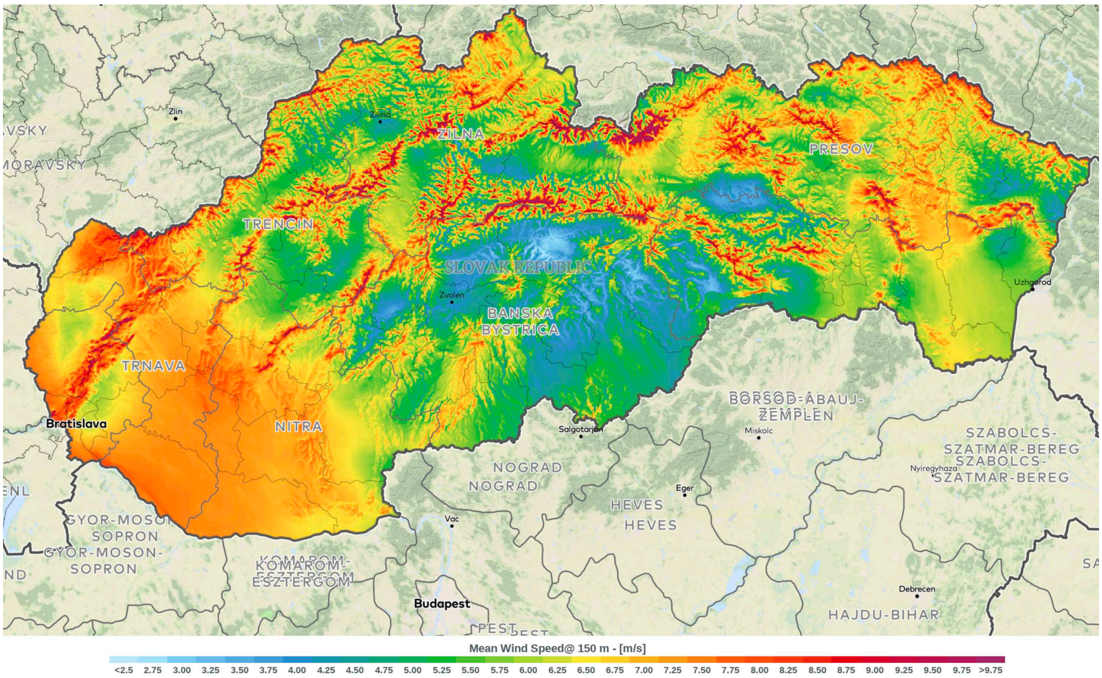

Figure 21: The Mean Wind Speed 150m above the Ground. Source: (Global Wind Atlas, 2020)

The formula of the wind power passing perpendicularly through a circular area is as follows:

$$P_{wind} = {}^{1}/_{2}\, \rho\, v^{3}\, \pi\, r^{2} \quad (1)$$

Where $\boldsymbol{P_{wind}}$ is the power of the wind measured in Watts, $\boldsymbol{\rho}$ is the density of dry air = 1,225 measured in kg/m^3 at average atmospheric pressure at sea level at 15°C, $\boldsymbol{v}$ is the velocity of the wind measured in m/s, $\boldsymbol{\pi}$ is 3,1416…, $\boldsymbol{r}$ is the radius of the rotor measured in m.

$$^1/_2 \times 1{,}225 \times 6{,}5^3 \times 3{,}1416 \times 85^2 = 381604654\,W$$

The Siemens Gamesa turbine with a rotor diameter of 170 m can catch 1,77 of 3,82 MW wind power when the wind blows at 6,5 m/s speed, (Figure 22). This refers to the efficiency of 46% at the wind speed 6,5 m/s.

$$\eta = \frac{P_{turbine}}{P_{wind}} \qquad (2)$$

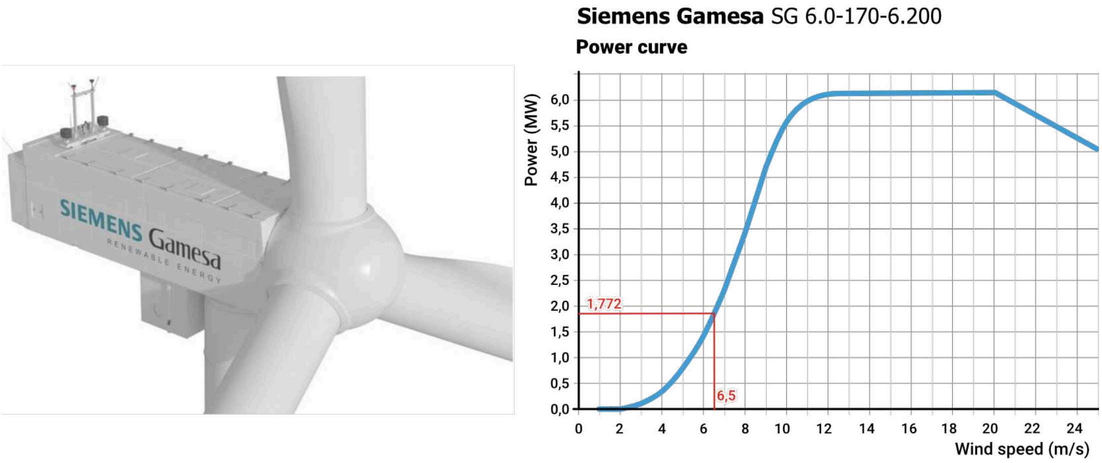

Figure 22: Power curve of Siemens Gamesa 170 6,2 MW wind turbine (own graph based on Siemens data, 2020)

For this case study, the nominal installing power of a 150 MW wind farm, respectively a net power of 148,8 MW, has been chosen in order to meet the triple electrolyser capacity. Then 24 wind turbines with a rated power of 6,2 MW will generate more than 450 GWh renewable electricity. According to the long-term measurement of the wind speed in the case location, the wind turbines can reach the capacity factor of 34,6 % as Table 6 summarises. It means that the wind turbines can run with 3029 Full Load Hours (FLH) annually. The capacity factor and the full load hours are defined as follows:*” The capacity factor is defined as the number of full load hours per year divided by the total number of hours per year (8760). Full load hours are calculated as the turbine’s average annual production divided by its rated power. The higher the* *capacity factor (correspondingly the number of full load hours), the higher the wind turbine's production at the chosen site."* (Morthorst & Kitzing, 2016: 23).

Table 6: The Wind Farm – the Technical Specification (own calculation based on data from Eurowind energy S/A. 2020)

Energy data	value	unit
Nominal power - renewables	150	MW
Nominal power - electrolyser	50	MW
Wind turbine rated power*	6,2	MW
Turbines	24	pcs
Net rated power	148,8	MW
Capacity factor (CF)	34,6%	%
Full Load Hours	3029	h/yr
Power generation	450,79	GWh/yr

* Low wind type IEC S

Economic Appraisal

The continual development of wind turbines brings more powerful and efficient turbines on the market. Scaling up the production reduces their initial costs, especially for the large developers. The large wind farm developers can usually offer special conditions for customers with favourable prices and service packages. Moreover, they have the most accurate and actual data directly from the producers. In order to provide precise economic calculation, the input data from the Danish Eurowind energy S/A were used.

Costs

Eurowind energy S/A confirms that specific investment costs of the wind turbine drop under the € 0,9 M per 1 MW. Together with the Balance of Plant (BoP) costs, € 0,15 M/MW, the total investments slightly overcome the one million level (€ 1,014 M). The BoP costs reflect the infrastructure and facilities without the turbine and all its elements. The BoP therefore mainly comprises the following items: the road upgrades or construction, the crane pads, the foundations, the substation, the civil and electrical work, the cabling to the substation, the connection to the grid, SCADA, the transformer station, etc. The costs of the design of the plant, permitting and the commissioning are estimated to be € 50 t per a MW installed. The CAPEX ($\boldsymbol{C_0}$) of 24 wind turbines with the total installing power of 148,8 MW ($\boldsymbol{P_{inst}}$) and the specific costs of €1,064 M per 1 MW installed ($\boldsymbol{C_s}$) is € 158,3 M, calculating as follows:

$$C_0 = C_s P_{inst} \quad (3)$$

The annual operation and maintenance costs (O&M) are 1,5% of CAPEX € 2,2 M, being indexed by 2% annually during the operation. Table 7 shows the costs structure of the wind farm.

Table 7: The Wind Farm – the Initial Costs (own table based on data from Eurowind energy S/A, 2020)

Costs	value	units
Specific investment costs*	0,864	M€/1 MW
Specific costs of BoP*	0,15	M€/1 MW
Specific costs of design, permits and commissioning*	0,05	M€/1 MW
Specific costs total*	1,064	M€/1 MW
CAPEX	158,3	M€
O&M (1,5% of CAPEX)	2,2	M€

* Surce: Eurowind energy S/A

Revenues

The annual revenues from the sale of electricity will vary each year depending on the share of the power supply to EC or/and the grid. The revenues from the sale to the grid depend on the final annual electricity price and the power sold. The final annual price of electricity consists of two parts: the fixed price of the power delivered directly to the EC for the price of € 40/MWh (EC price), and the annual weighted average price of the excessed electricity delivered to the grid (grid price). The grid price in the H2 off-peak and the H2 flexi scenario is defined as the weighted average of the hourly spot market prices and the amount of the electricity sold to the grid in the specific hour throughout the year. The grid price in the H2 max scenario is defined as the weighted average of the future annual peak-load or the off-peak load market prices and the amount of the electricity sold to the grid in the specific hour throughout the year. Thus, the revenues depend on the particular operational strategy and the development of the price for electricity on the market.

A wind farm can benefit from a long-term purchase contract with the EC operator by which the fixed price is agreed. In this case, the price in the amount of € 40/MWh is recommended. The fixed price is near to the off-peak price on an annual basis.

Table 8: The Slovak Power Market Price in 2019 (OKTE, 2020)

	Peak-load	Base-load	Off-peak
Price 2019 (€/MWh)	46,01	41,50	38,99

For the calculation of the grid price, the reverse-simulation method has been chosen using the data from 2019. Data have been derived from the database of the Short-term Electricity Market Operator - OKTE, a.s. (OKTE, 2020).

The reverse simulation based on the data from 2019 shows that the **H2 off-peak scenario** generates the revenues from the grid power sale in the amount of € 13,3 M and € 6,4 M from the EC sale. Total revenues in the amount of € 19,4 M refer to the final price of € 43,57/MWh.

The **H2 fexi scenario** earns € 12,7 M and € 7,0 M respectively, in total € 19,7 M, and the final price € 43,74/MWh is a bit higher than in the H2 off-peak scenario.

The **H2 max scenario** achieves almost the balanced incomes from the grid and EC in the amount of € 9,1 M and € 9,7 M respectively. In total € 18,8 M is the worst result, however, the annual power delivery to the electrolyser is by 52%, respectively by 38% higher.

The revenues and the final purchase prices for each scenario summarises Table 9. The revenues of electricity sale $\boldsymbol{R}$ are calculated as follows:

$$R = R_g + R_e \tag{4}$$

Where $\boldsymbol{R_g}$ are revenues of electricity sale to the grid and $\boldsymbol{R_e}$ are revenues of electricity sale to the EC.

Table 9: The Revenues based on 3 Different Demand-supply Strategies (own calculation)

Sale	H2off-peak	H2flexi	H2max
Grid sale (M€)	13,3	12,7	9,2
EC sale (M€)	6,4	7,0	9,7
Total sale (M€)	19,6	19,7	18,8
Final price (€/MWh)	43,57	43,74	41,79

Financial analysis

A Dynamic Investment Analysis (DIA) has been chosen for the evaluation of the economic performance of the wind farm. The DIA uses a concept of the Long-Run Generation Costs of electricity ($LRGC_{EL}$), and the Net Present Value (NPV) to assess the case. The NPV in general is a method to translate multiple cash flows, occurring at different times in the future, into one present value. For the calculation, all negative cash flows are opposed to the positive cash flows of a project. Discounting the net cash flows of each period with the discount rate, a rate that represents the costs of capital, and forming the sum of the results, leads to the NPV (Schwaiger, 2016: 55).

The $LRGC_{EL}$ are the marginal costs where the NPV of the investment remains zero. It represents the lifetime average costs of electricity of the project. In other words, $LGRC_{EL}$ leads to the necessary purchase price of electricity, where the project remains profitable at the end of the investment period, as the following formulas explain.

$$LRGC_{EL}=\left(\frac{\alpha_c}{EL}\right) \quad (5)$$

Where α_c is the annuity of costs and EL is the annual electricity generation. The annuity of costs are defined as follows:

$$\alpha_c = CRF\ NPV_c \quad (6)$$

where $\boldsymbol{\alpha_c}$ is the annuity of costs, $\boldsymbol{NPV_c}$ is the net present value of all future costs over the life of the investment discounted to the present and $\boldsymbol{CRF}$ is the capacity recovery factor, which is defined as follows:

$$CRF = \frac{r\,(1+r)^T}{(1+r)^T-1} \quad (7)$$

where $\boldsymbol{r}$ is the discount rate or the Weighted Average Cost of Capital (WACC), and $\boldsymbol{T}$ is the investment horizon in years.

The net present value of the costs is the value of all future positive and negative cash flows over the life of the investment discounted to the present. It provides a method for evaluating and comparing of the capital projects with the cash flows spread over the time that can be calculated as follows:

$$NPV = \sum_{t-1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (8)$$

where t is the year-count, C_t is the cash flow in the year t in M€, and C_0 is the initial investment in M€.

The case study assumes the investment horizon of 20 years with capital costs in the amount of 7,5%. The lifetime of the gearbox is about 12 years and the control unit about 10 years. The gearboxes will be refurbished, and the control units updated. The overview of the input financial data is summarised in Table 10. The calculation of the dynamic investment analyses of the H2 max scenario can be seen in Appendix 4.

Table 10: The Wind Farm Input Data for the Financial Analysis (own table based on data from Eurowind energy S/A, 2020)

Data Description	Value	Unit
Initial investment costs (CAPEX)	158,3	m€
Discount rate (WACC)	7,5%	/yr
O&M (incl. all variable costs)	2,2	m€/yr
Real escalation of O&M Costs	2%	/yr
Gearbox Replacement Cost	5%	
Gearbox Lifetime	15,0	yr
Control system Update	2%	
Control system Lifetime	10,0	yr

By substituting the input values in the formulas, the $LRGC_{EL}$ of the wind farm remains below the value of the final purchase price within all three scenarios, as Table 11 clearly shows. The lower $LRGC_{EL}$ than the purchase price indicates the profitable operation on electricity market without the needs of any incentives.

Table 11: Wind farm LRGC & NPV (own calculation)

Data Description	H2off-peak	H2flexi	H2max
Final selling price (€/MWh)	43,57	43,74	41,79
LRGC (€/MWh)	41,69	41,69	41,69
Price diference	4,5%	4,9%	0,2%
NPV (M€)	8,665	9,445	0,444

The price difference is slight and depends on market prices. However, the future products at the Power Exchange Central Europe indicate the rising trend, as Table

12 illustrates. This means that the operation would be more profitable in 2020 and 2021 compared to 2019. However, the price development is unpredictable in the long-term horizon.

Table 12: The Power Price Development (Power Exchange Central Europe, 2020)

	PRICE (€/MWh)			CHANGE (compare to 2019)		
Source	**Peak-load**	**Base-load**	**Off-peak**	**Peak-load**	**Base-load**	**Off-peak**
Price 2019 (OKTE)	46,01	41,50	38,99			
Price 2020 F PXE SK BL&PL CAL-21	56,30	45,77	39,91	22%	10%	2%
Price 2021 F PXE SK BL&PL CAL-22	61,01	48,32	41,26	33%	16%	6%

6.5 Electrolyser

This master thesis is focused on the renewable hydrogen production through the water electrolysis, as the most promising way of production of hydrogen from the current point of view. An electrolyser is a device where during the process of electrolysis water is split into the molecules of hydrogen and oxygen using the direct current electricity. If the renewable electricity is used, the renewable hydrogen, also known as clean or green hydrogen, is produced without any net emissions.

The electrolysis, as the electric-chemical process, has been used from the 19th century in many applications. The matured alkaline electrolysis dominates, especially in the chemical industry. Many years of development and operation of alkaline electrolysers have led to the lower prices, increased efficiency and the extended life. The investment costs have fallen by 60% since 2010 and are expected to be reduced by a half by 2030. At the same time, the PEM electrolysers show better parameters in power ramp-up, and start-up time (Table 13), which is essential referring the integration with the variable renewable electricity sources. These characteristics predetermine PEM for the provision of the ancillary services for the electricity system and the provision of the additional revenues.

Table 13: The Dynamic Properties of the Alkaline and PEM Water Electrolysis. Source: (Bertuccioli et al., 2014: 66)

	Alkaline water electrolysis	**PEM water electrolysis**
Start-up time [minutes]	20 - several hours	5 - 15
Ramp-up time [%/sec]	0,1 - 25	10 - 100
Ramp-down rate [%/sec]	25	10 - 100

The electrolysers are divided into the categories according to the electrolyte material used and the temperature at which they are operated. The group of the low-temperature electrolysers includes the proton exchange membrane (PEM), the alkaline (AE), and the anion exchange membrane (AEM) electrolysers. The high-temperature electrolysers comprise the highly efficient solid oxide electrolysers (SOE), however, they are currently still at the advanced R&D stage and have not been launched to the market yet. (Hydrogen Europe, 2020b).

The selection of the appropriate electrolysis technology depends on the requirements and the context. The outstanding dynamic characteristics of a PEM electrolyser are essential for a Power-to-Hydrogen plant. Thus, the 50 MW PEM electrolyser will be further evaluated and used in the Power-to-Hydrogen plant case study. The following table shows the main characteristics of the three different type of electrolysers. The fundamental input data for the technical-economic appraisal used in this master thesis were derived from the red highlighted parameters shown in the Table 14.

Table 14: The Techno-economic Characteristics of the Individual Electrolyser Technologies. Source: (IEA, 2019)

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	2019	2030	Long term	2019	2030	Long-term	2019	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60 2024: 63	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000 70 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					

The PEM Electrolyser

A PEM electrolyser system consists of a stack and a balance of plant (BoP). The stack consists of the cells with the membrane electrodes assembly (MEA) clamped between the two porous current collectors. The two separator plates cover the current collectors and separate the two adjoining cells. The MEA consists of two catalytic layers, electrodes, an anode and a cathode connected to the external direct current power source. A thin (≈ 0,1 mm) proton-conducting polymer membrane is placed between the electrodes and serves as a solid electrolyte as explained in Figure 23. The membrane has two main functions: to carry the ionic charges and to separate the outcomes of electrolysis in order to prevent the spontaneous exothermic recombination of oxygen and hydrogen back into water. The typical material for the membrane is the perfluorosulfonate polymer due to its mechanical durability, thermal and chemical stability, and good proton conductivity. The disadvantages are high costs and difficult recycling because of the fluorine present in the structure. The electrodes are usually made of the noble metals, such as iridium or platinum (Lappalainen, 2019: 17, 18). The following half-cell reactions occur at the anode and cathode:

$$anode: \quad H_2O_{(l)} \rightarrow \frac{1}{2}O_{2(g)} + 2\,H^+ + 2e^-$$

$$cathode: 2H^+ + 2e^- \rightarrow H_{2(g)}$$

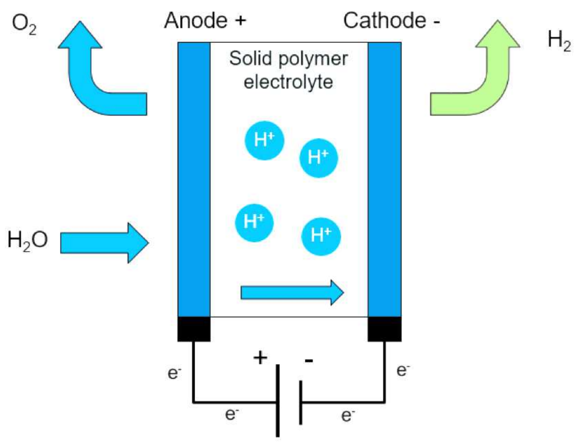

Figure 23: The Schematic Cross Section of MEA. Source: (Lappalainen, 2019)

The electrolysers consist of a stack skid and a balance of plant (BoP) comprising the units such as a water supply with the water purification unit, a substation, a transformer, a rectifier, a condenser, a chiller, a hydrogen purifier, a heat exchanger, a pump skid, an oxygen separator and an air blast cooler, as Figure 25 shows. A modular based system is capable of the large-scale hydrogen production. The tap water, as an input for the electrolyser, must be purified, as the water impurities degrade the MEA and shorten the lifetime of the stack skid. The output hydrogen consists of water and must be both dry and purified. All the system is controlled and kept in the optimal thermal and pressure conditions. The 3D electrolyser system scheme by ITM Power shows Figure 24. The Layout of a PEM electrolysis system can be found in Appendix 2.

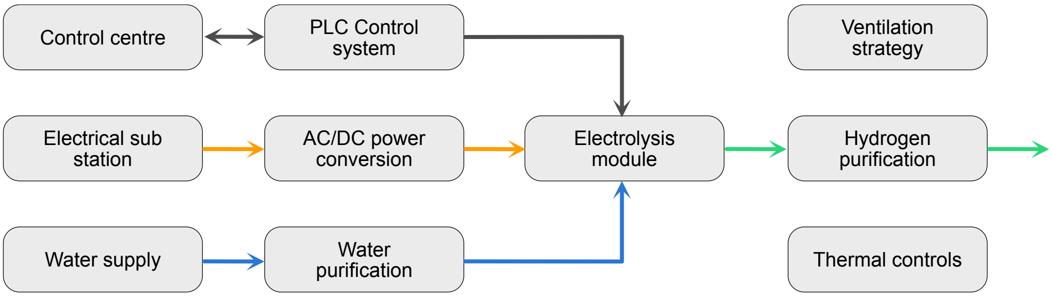

Figure 24: The Electrolyser System Diagram. Source: (ITM Power, 2020)

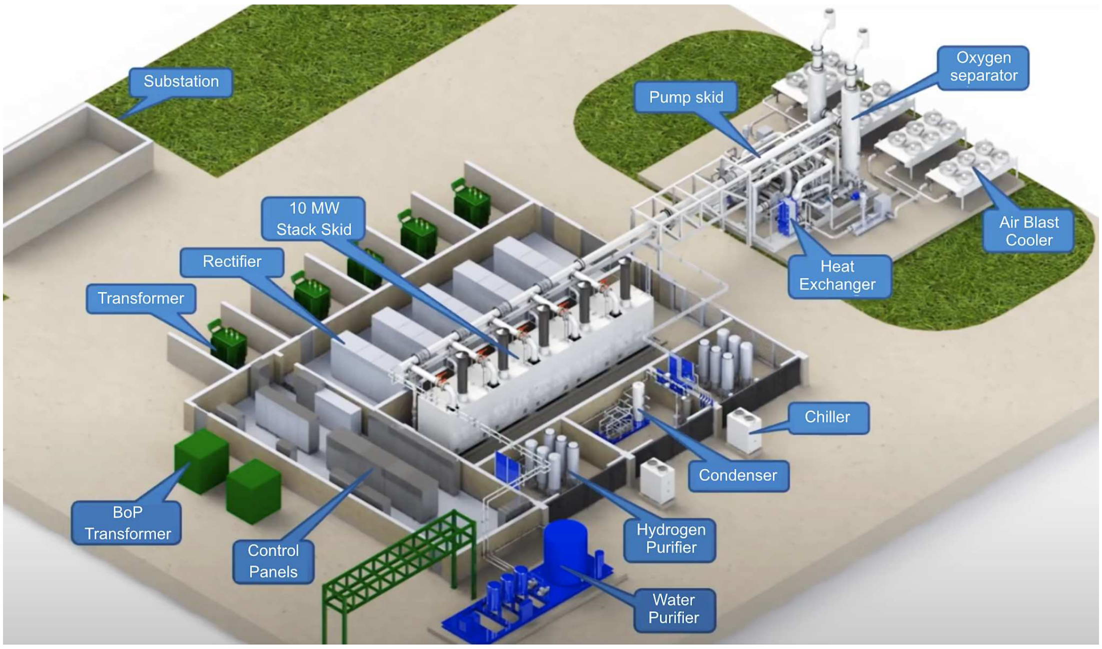

Figure 25: The PEM electrolyser 10 MW – the REFHYNE Project in Rhineland, Germany. Source: (ITM Power, 2020)

As an example, ITM Power, the producer of electrolysers, designs a large system of an electrolyser based on the modules of three power stacks. Each 3-stack module is rated by 2MW power at the beginning of its life. For this case study, a 50 MW electrolyser system consists of 25 modules. Each 2MW module can operate independently from one another allowing greater flexibility in the load control and the rolling maintenance (ITM Power, 2020).

The Proton Exchange Membrane (PEM) electrolysers have been recently launched to the market in scales of tens of MW. A 6 MW electrolyser was put in commission in 2019 in Linz, Austria. This Austrian H2FUTURE project produces hydrogen for the needs of the steel industry, while the ancillary services for the grid are being examined. Within the Danish HYBALANCE PEM project hydrogen has been generated since 2018. The 10 MW PEM is being prepared in Germany within the REFHYNE project. Some new projects have been recently announced within the EU with a scale from tens to hundreds of MW. The European Commission is planning to deploy 6 GW of the renewable hydrogen electrolyser capacity by 2024.

The Technical Appraisal

The necessary technical input data for the execution of the case study were retrieved from the IEA's report "The Future of Hydrogen". The PEM EC efficiency of 63% was chosen as the mean value out of the lowest efficiency in 2019 (56%) and the highest value in 2030 (68%), as Table 12 shows (IEA, 2019b). The lifetime of the stack in the amount of 70 000 hours with the 10%-degradation at the end of its lifetime was considered in the economic calculation too. The degradation defines the percentage of the loss of efficiency when run at the nominal capacity. For example, when the capacity factor of EC is 40%, then FLH is 3504 and the degradation is 0,5% annually. As a result, extra 0,5% of electricity is needed every year to produce the same amount of hydrogen. A Power-to-Hydrogen plant is equipped with a high-pressure compressor with a capacity to store a volume of the 24-hour production of hydrogen. The 300-bar compressed hydrogen can be filled in the truck cistern and transported to the hydrogen refuelling stations. Until the times when hydrogen transport is fully launched on the Slovak market, the electrolyser can produce the green hydrogen for the ammonia plant. As a result, an approximately 1 km long low-pressure hydrogen pipe will connect the electrolyser with the near ammonia plant. For this purpose, a pressure of 20 bar at the output of the electrolyser is enough for the pipe transport. The overview of the basic technical specifications is shown in Table 15.

Table 15: The Technical Specifications of Electrolysis (own calculation)

Data Description	Value	Unit
Rated Capacity	50	MW
Efficiency (LHV)	63%	
Stack lifetime	70000	h
Stack degradation at the end of lifetime	10%	
Annual stack degradation	0,7%	

One of the most important factors influencing the economic activity of the EC is the FLH, or the capacity factor. The highest value of FLH, 4711, is reached in the H2 Max scenario, due to the continuous operation of the electrolyser as Table 16 shows. In contrast, the H2 off-peak and the H2Flexi scenarios reach FLH only in the amounts of 3062 and 3393, however, they can supply the electricity to the grid when needed; thus, they integrate the renewables more efficiently. The H2Max scenario can produce 4452 t of the renewable hydrogen per a year, which will be sufficient to supply the entire hydrogen transport sector by 2028, providing the consumption reaches the level of 3400 t.

The electrolyser can achieve the theoretical production of hydrogen in the amount of 8278 tons subject to a full annual operation. As the supply-demand scenarios have shown, the capacity factor (FLH) depends on the availability of the renewable power. Thus, in this case study EC utilises its capacity from 35% to 54% on the level of the long-term annual average. In the actual operation, the number of FLH can vary depending on the primary wind power availability from year to year, or on the demand of the customers purchasing hydrogen.

The MEA in the electrolyser is exposed to the severe conditions and works under high pressure and at high temperatures. Any impurity in the incoming water can reduce the life of the stack. For PEM EC, the service life is 70,000 h subject to a full load operation. When the energy costs increase by 10% per a unit of the hydrogen produced, the stacks will be replaced. Therefore, the stack life depends on the EC load. When the H2Max scenario is applied, the replacement after 15 years will be executed, however, in case of the H2 off-peak electrolyser, it can work with the original stack for almost 23 years. The price of the electrolysers is expected to fall by 50% in 2030, which means that the replacement will not be as costly. The estimated specific costs are € 200 per a kW. After the replacement, the electrolyser system efficiency will jump abruptly to about 70%. Table 16 summarises the EC utilisation and shows that the production of hydrogen and the stack replacement depend directly on one another. The values of FLH and the capacity factor are the net values reached after the deduction of the annual 5-day-maintenance break, during which the EC is off.

Table 16: The Utilisation of Electrolysis (own calculation)

Revenues	H2off-peak	H2flexi	H2max	Unit
Full Load Hours (FLH)	3 062	3 393	4 711	h/yr
Capacity factor	35%	39%	54%	
Hydrogen production	2 894	3 207	4 452	t/yr
Stack replacement after	22,9	20,6	14,9	yr

The Compressor & Daily Storage

The nominal power of the 300-bar compressor and the daily storage have been designed based on the Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe (Christensen, 2020: 18–20) as follows:

$$P = Q\left(\frac{1}{24 * 3600}\right)\frac{ZTR}{M_{H_2}\eta}\frac{N\gamma}{\gamma - 1}\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{N\gamma}} - 1\right) \quad (9)$$

$\boldsymbol{Q}$ is the flow rate (22 680 kg/day), $\boldsymbol{P_{in}}$ is the inlet pressure of the compressor (18 bar), $\boldsymbol{P_{out}}$ is the outlet pressure of the compressor (300 bar), $\boldsymbol{Z}$ is the hydrogen compressibility factor (1,03198), $\boldsymbol{N}$ is the number of compressor stages (assumed to be 4 for this work), $\boldsymbol{T}$ is the inlet temperature of the compressor (310,95) K), $\boldsymbol{\gamma}$ is the ratio of specific heats (1,4), $\boldsymbol{M_{H2}}$ is the molecular mass of hydrogen (2,15g/mol), $\boldsymbol{\eta}$ is the compressor efficiency (taken as 75%), the universal constant of ideal gas $\boldsymbol{R}$ = 8,314 J/molK . The $\frac{1}{24 * 3600}$ share is the necessary factor that converts daily units into seconds.

After substituting the values of the formula, the power of the motor compressing hydrogen from 18 to 300 bar is 1,58 MW.

The Economic Appraisal

Costs

The costs for the electrolyser system include the capital expenditure (CAPEX) and the operation and maintenance costs (hereinafter referred as “O&M”, “OPEX” or “Operational Expenditure”).

The Capital Costs

The capital expenditures consist of the costs of the electrolyser system including the costs of the electrolyser unit, the hydrogen compressor & storage, and the balance of plant. The costs of general facilities in the amount of 15% from the EC system costs comprise the costs to construct the access road, the site arrangement, the buildings and the power and water grid connections. The engineering, permitting, and the commissioning are estimated in the amount of 5% of the EC system costs. The reserve for the contingencies creates 5% and for the working capital and miscellaneous it is 2,5% of the EC system costs. As the PEM EC is a new facility dealing with the explosive H2 in case of a leak, siting costs are added in the amount of 5% from the total costs. The facility siting costs involve the potential damage in case of fire, explosion or a chemical incident in an occupied building in the work area (Torres, 2019). The specific costs in the amount of € 600/kW of the electrolyser have been derived from the Clean Hydrogen Monitor webpage by the Hydrogen Europe, which provides a detailed overview of the current status of the clean hydrogen technologies in Europe (Hydrogen Europe, 2020a: 101). The specific costs of the hydrogen compressor and the storage according to (Christensen, 2020: 20) are € 276/kW and BoP € 50/kW. Table 17 summarises the CAPEX in detail. The calculation also includes a stack replacement after a certain period which depends on the annual utilisation of EC. The lower intensity of load of the EC means the longer lifetime of the stack in EC. The stack replacement costs create a 1/3 from the original costs of the EC system because only a part of the EC system will be replaced, as well as since a reduction of EC costs by a half is expected after 10 years.

Table 17: The Capital Costs of Electrolysis (own calculation based on data from Hydrogen Europe, FCH JU and Torrez, 2020)

Capital Costs	Specific costs (€/kW)	Costs (M€)
Electrolyser unit	600	30,0
Hydrogen compressor & storage (C&S)	276	13,8
BoP	50	2,5
Total Electrolyser system	**926**	**46,3**
General facilities (15%)	139	6,9
Engineering, permitting, start-up (5%)	46	2,3
Contingencies (5%)	46	2,3
Working capital and miscellaneous (2,5%)	23	1,2
Total capital	**1181**	**59,0**
Siting factor (5%)	59	3,0
Total	**1240**	**62,0**
Stack replacement costs (1/3 original EC)	200	10,0
BoP+C&S general maintenance (20%)	65	3,3

The O&M costs

The O&M costs consist of fixed and variable operating costs and maintenance. The fixed operational costs, in this case, are the personnel costs, the annual payments for the service package and the services that are independent of the operation. In the case of the wind farm, there are no variable costs in order to no fuel inputs. The amount of O&M costs is derived from the investment costs in the amount of 4% each year (Torres, 2019). However, the Hydrogen Europe estimates O&M to be 2% from CAPEX. The 4% O&M was considered in the calculation. These costs are this indexing in this case study, and they escalate by 2% each year, as is shown in the Table 18. The electricity and water costs are excluded from the O&M costs. The main portion of the electricity costs is created by the electrolyser itself, but a small share goes to BoP- the water treatment, pumps, coolers and a high-pressure compressor.

Table 18: The Fixed Costs of Electrolysis (own calculation)

O&M (4% from CAPEX)	2,479	M€/yr
Real escalation of O&M Costs	2%	/yr

This case study assumes that the wind farm directly delivers the renewable power to the EC for the agreed purchase price (EC price) in the amount of € 40/MW. The EC price is a fixed price, exempt from the fees and taxes during the investment horizon of 20 years. The electrolyser uses the tap water. When the EC works on the full load, it consumes 2,4 l of water per a second. The EC annually splits 26,046 to 40,066 m^3 of tap water for the price in the amount of € 1,30 /m^3. The total variable costs are shown in Table 19. The $\boldsymbol{C_e}$ electricity costs are calculated as follows:

$$C_e = (P_{EC} + P_{CO})\ EC_{pp}\ FLH \tag{10}$$

Where $\boldsymbol{P_{EC}}$ is the nominal power of electrolyser (50 MW), $\boldsymbol{P_{CO}}$ is the nominal power of compressor (1,58 MW), $\boldsymbol{EC_{pp}}$ is the electricity purchase price from the RES (EC power price) (€ 40/MWh), and $\boldsymbol{FLH}$ is the full load hours which fluctuate depend on the scenario chosen.

The $\boldsymbol{C_W}$ water costs parameter is calculated as follows:

$$C_W = W_{pp}\ H\ W \tag{11}$$

$\boldsymbol{W_{pp}}$ is the tap water purchase price (1,3 €/m^3), assuming that 1 m^3 of water = 1 t, and $\boldsymbol{H}$ is the annual hydrogen production in tons. $\boldsymbol{W}$ is the weight of water (8 kg) which is needed to produce 1 kg of H_2, and 1 kg of H_2O gets lost during the process, and $\boldsymbol{W}$ is equals 9.

Table 19: The Variable Costs of Electrolysis in M€/year (own calculation)

Variable costs	H2off-peak	H2flexi	H2max
Power costs - electrolysis	6,125	6,787	9,422
Power costs - compressor	0,203	0,225	0,313
Water costs	0,034	0,038	0,052
Total	**6,362**	**7,050**	**9,787**

The Electrolysis Outputs

There are four outputs from electrolysis that can be sold on the market: hydrogen, oxygen, heat and the ancillary services for the transmission grid operator. Hydrogen was described in chapter 4.1 in detail. The means of utilisation of oxygen, ancillary services and heat are evaluated in the next paragraphs.

Oxygen

Along with hydrogen, the PEM electrolyser also produces oxygen (O_2) from the water electrolysis. Per every mol of H_2 produced, a half mol of O_2 is generated. In other words, there are 8 kg of oxygen per a kg of hydrogen produced.

The global demand of oxygen was estimated to be USD 19,2 billion in 2017. The oxygen market in Slovakia is limited. One of the main suppliers of the technical gases in Slovakia, Messer Tatragas, s.r.o., supplied its clients with 15 million kilograms of technical oxygen and 3 million kilograms of medical oxygen in 2019. (tuochIT, 2020)

There are two main fields of the utilization of oxygen. Firstly, the medical purposes where the pure oxygen is produced by a low-temperature fractional cryogenic distillation of the liquefied air. Secondly, the electrolysis can produce oxygen for the technical purposes, e.g. for the autogenous welding and cutting of metals. The largest amount of oxygen is consumed in the oxygen converters in the steel production and in other high-temperature processes, where it improves the quality of the fuel combustion and at the same time saves fuel by increasing the efficiency. Oxygen from the electrolysis is suitable for a technical application.

The price for one ton of O_2 varies in the literature and depends on the form (gaseous/liquid) and the end-use application. It varies from € 24,5/t for the industrial purposes to € 250/t for the liquid oxygen for the medical ones. Significantly lower purchase price was assumed for the utilisation in a large-scale extent, such as the pulp mills. (Lappalainen, 2019: 29).

While price for oxygen is negligible compared to the price for hydrogen, every additional yield is needed to achieve as low levelised costs of hydrogen as possible. Oxygen, as a by-product, can be sold in the Slovak market as well. For the purposes of this thesis, the price in the amount of € 25/t will be used. The following equation calculates the annual revenues $\boldsymbol{O_{rev}}$ from the oxygen sale:

$$O_{rev} = \frac{O_{SP}\ H_{pro}\ O_{pro}}{2} \quad (12)$$

where $\boldsymbol{O_{SP}}$ is the purchase price of oxygen in the amount of € 25/t, $\boldsymbol{H_{pro}}$ is the annual production of hydrogen in tons a year, and $\boldsymbol{O_{pro}}$ is 8 kg of oxygen produced per a kg of hydrogen by the water electrolysis.

The annual revenues varied between 0,289 and 0,446 M€ per a year depending on the scenario chosen, estimating that a half of the oxygen released from the process can be sold. The share of the revenues is minimal, only 2,4% from the total revenues.

The Balancing and Ancillary Services

"Electricity balancing means all actions and processes, on all timelines, through which transmission grid operator (TSO) ensure, in a continuous way, the maintenance of system frequency within a predefined stability range. There are two types of balancing services: balancing capacity and balancing energy:

- *Balancing capacity means a volume of reserve capacity that a balancing service provider (BSP) has agreed to hold and in respect to which the BSP has agreed to submit bids for a corresponding volume of balancing energy to the TSO for the duration of the contract,*
- *Balancing energy means energy used by TSOs to perform balancing and provided by a BSP"* (ENTSO-E, 2020).

The large grid connection capacity via the existing transformer station can be used to deliver the ancillary services to TSOs. The electrolyser, as the BSP, can provide both, the balancing capacity and the balancing energy. After the discussion with an expert from SEPS, a.s. (the national TSO), the EC can currently offer only one type of the grid service, the increase of load. In this case, the EC will offer all its available capacity every hour throughout the year. For the operation of the electrolyser, the ancillary service has the priority before the renewable power supply. In case the wind farm is supplying EC and at the same time the grid service is activated, the overall surplus of the renewable electricity over the capacity of the electrolyser must be curtailed or used for other applications, e.g. heating water in order to heat the greenhouse farms. In praxis, the activation occurs only several times a year. Currently, the TSO offers € 3/MW/h for the balancing capacity. This price is used in the calculation. In the future, the Frequency Restoration Reserve (FRR) service will include the Consumption Increase service, as well as all the tertiary services used in Slovakia today. According to Article 3(2)(7) of the Network Code on System Operation the FRR is defines as follows:" *'frequency restoration reserves' or 'FRR' means the active power reserves available to restore system frequency to the nominal frequency and, for a synchronous area consisting of more than one Load-Frequency Control Area, to restore power balance to the scheduled value."* (EUR-Lex, 2017). The Slovak TSO, SEPS, a.s., currently orders only 10 MW of the Consumption Increase service in Slovakia. Thus, only 20% of the total EC capacity can be granted to the ancillary services in this case. The overview of the range of the average availability of the ancillary services from 2005 to 2018 in the Slovak power transition system is illustrated in the following Figure 26. The figure shows the small share available for the EC.

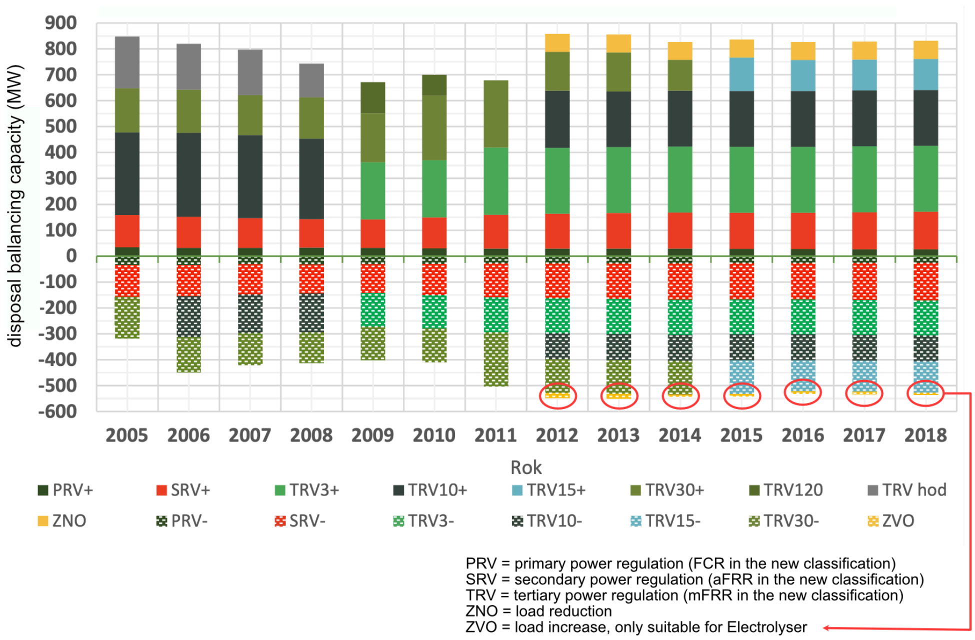

Figure 26: The Range of the Average Availability of the Ancillary Services from 2005 to 2018 in Slovakia. Source: (SEPS, 2020, own translation)

As a result, nowadays the EC can offer merely the limited ancillary services. The load increase is the only service that can be offered to TSO. The low price of € 3/MW/h and the limited capacity of 10MW will earn only M€ 0,259 annually. This is only from 1,42 % to 2,15% of all the revenues depending on the chosen scenario.

For the future, EC can also deliver the valuable Frequency Containment Reserve (FCR), but today the FCR is a symmetric product, and EC is not able to deliver the symmetric product and the active power supply. Currently, the FCR is rewarded by € 41,12 /MW/h. According to Article 3(2)(6) of the Network Code on System Operation the FCR is defines as follows: *"Frequency containment reserve (FCR) in the European Union Internal Electricity Balancing Market means operating reserves necessary for constant containment of frequency deviations (fluctuations) from the nominal value in order to continually maintain the power balance in the whole synchronously interconnected system."* (EUR-Lex, 2017)

The Waste Heat Utilisation

The probable location of a large electrolyser is far away from the urban areas that do not allow to use the waste heat for the heating of the buildings, however, the heating of the greenhouse farms seem to be feasible. The greenhouse needs a heating medium with a temperature of 50 to 60° C at the entrance. A 1,7 MW_{th} heat source requires 1 ha of the greenhouse area and 0,55 MW of electricity for the lighting. The profitable farming requires at least 3 ha of the greenhouse area that will be heated up for six months a year. Approximately a half of the waste heat at a convenient temperature can be captured and used from the electrolyser. Theoretically, the electrolyser with the efficiency of 63%, converts 37% of electricity into the heat. A half of the waste heat, 18,5%, can be captured and used. The 50 MW electrolyser can produce 9,5 MW_{th} of heat for sale in a full load operation. Theoretically, a 5-ha greenhouse can be heated with a 50 MW electrolyser, but in praxis, the optimal situation when 9,5 MWh_{th} is available rarely occurs due to the variable electricity production from the wind. Therefore, the greenhouse needs a back-up heating system to cover the lack of heat from EC or to reduce the heating area in greenhouses. A 3-ha greenhouse needs a 6,5 MW_{th} heat source in the coldest winter periods when the outside temperature drops under -15 °C. The reduction of the greenhouse area from 5 to 3 hectares and a gas boiler as the back-up heat source is the optimal solution in this case. Referring the calculations, assumably a 1/3 of the available heat (14,5 GWh_{th}/yr) will be sold to the greenhouse company for the price of € 20/MWh_{th} during the six months of a year. For better understanding, the following table shows the annual heat and the electricity demand for 1 ha of a greenhouse in which flowers are grown. The following equation calculates the annual revenues $\boldsymbol{T_{rev}}$ from the sale of heat:

$$T_{rev} = T_{SP}\, T_{capt}\, T_{seas} \tag{13}$$

where $\boldsymbol{T_{SP}}$ is the purchase price of heat € 20/MWh$_t$, $\boldsymbol{T_{capt}}$ is the annual amount of the captured heat from electrolyser in MWh$_t$, and $\boldsymbol{T_{seas}}$ has the value of 0,5 expressing the half-year contract for heating of the greenhouses.

$\boldsymbol{T_{capt}}$ is calculated as follows:

$$T_{capt} = FLH_{EC}\, P_{EC}\, (1 - \eta_{EC})\, 0{,}5 \tag{14}$$

where $\boldsymbol{FLH}$ is the full load hours of EC, $\boldsymbol{P_{EC}}$ is the rated power of EC and $\boldsymbol{\eta_{EC}}$ is the efficiency of EC. About ½ of the heat can be captured from EC. As a result, the EC can benefit from the sale of heat to a greenhouse farm in the amount of only M€ 0,189 to M€ 0,291 annually. It refers to the share of 1,6% on the total revenues in every scenario.

Table 20: The Electricity and Heat Demand for 1 ha of a Greenhouse Farm (retrieved from Daniel Gerbel, the owner of greenhouses 2020)

ELECTRICITY

Month	Electricity (MWh)	Daily average
1	409	13
2	370	13
3	217	7
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	279	9
11	396	13
12	409	13
Total	**2080**	

HEAT

Month	Heat (MWh)	Daily average
1	992	32
2	706	25
3	434	14
4	252	8
5	174	6
6	0	0
7	0	0
8	0	0
9	180	6
10	434	14
11	756	25
12	992	32
Total	**4919**	

The Revenues from the EC Outputs

The sale of hydrogen creates 94% of the revenues. The revenues from the sale of hydrogen ($\boldsymbol{H_{rev}}$) are calculated as follows:

$$H_{rev} = H_{pro}.H_{SP} \tag{15}$$

Where $\boldsymbol{H_{pro}}$ is the volume of hydrogen produced in each scenario and $\boldsymbol{H_{SP}}$ is the purchase price of hydrogen in the amount of € 4/kg.

The total revenues also differ in each scenario, as the following Table 21 presents.

Table 21: Revenues from the Electrolysis in M€/year (own calculation)

	H2 off-peak	H2 flexi	H2 max
Hydrogen Sale	11,576	12,827	17,807
Oxygen Sale	0,289	0,321	0,445
Heat Sale	0,189	0,209	0,291
Ancillary services	0,259	0,259	0,259
Total revenues	**12,314**	**13,616**	**18,802**

Financial analysis

For the electrolyser analysis, the same investment horizon of 20 years has been chosen for both the dynamic investment analysis as for the wind farm. The analysis counts with a 7,5% discount rate. The same method has been chosen to assess the EC economic performance, where NPV and LRGC indicate either a profit or a loss. In the literature, the concept of LCOH is used rather than LRGC. Both indicators are defined by the same formula. One of the main objectives of this master thesis is to find out if the LCOH can be lower than € 4/kg. LCOH is calculated as following:

$$\text{LCOH} = \left(\frac{\alpha_C}{H_{pro}}\right) \tag{16}$$

Where $\boldsymbol{\alpha_C}$ is the annuity of costs, and $\boldsymbol{H_{pro}}$ is the annual hydrogen production.

The annuity of costs is calculated as follows:

$$\alpha_C = NPV_{cost} - NPV_{oxygen} - NPV_{heat} - NPV_{ancillary} \tag{17}$$

where $\boldsymbol{NPV_{cost}}$ is the NPV of total costs, $\boldsymbol{NPV_{oxygen}}$ is the NPV of the oxygen revenues, $\boldsymbol{NPV_{heat}}$ is the NPV of the heat revenues, $\boldsymbol{NPV_{ancillary}}$ is the NPV of the ancillary services revenues.

When calculating LCOH, the annuity of costs is reduced by the net present value of the incomes from the sale of oxygen, the heat and the provision of the support services. Thus, the side revenues from the sale of the other products decrease the price of hydrogen. The higher the revenue from the sale of the ancillary products and services, the lower the price of hydrogen. The original assumptions counted with a more significant share of the incomes from the ancillary services on the total share, but after the discussion with SEPS, the national TSO, EC does not fulfil the strict conditions for delivering the profitable services today, such as FCR of FRR.

As a result, LCOH is higher in every scenario than the expected € 4,00/kg of H_2. The sale of the ancillary products and services is not able to decrease LOHC due to its negligible share of 7% on the total incomes, as explained in detail in the next chapter.

Forecast of the Price parity of Green and Grey Hydrogen

Today, any industrial customer would not be willing to pay 2-3 times more for the green hydrogen to replace the grey one (Hydrogen Europe, 2020a: 31). However, the trend of growing CO_2 costs indicates that the price of fossil-based hydrogen will grow. If the green hydrogen costs 3 €/kg in 2030 and the natural gas cost doubles, then the CO_2 ETS price must achieve 111 €/t to reach the price parity of the green to grey hydrogen as Table 22 presents.

Table 22: The Green - Grey Hydrogen Parity in 2030 (own calculation)

	2020	**2030**	**units**
Grey hydrogen production - OPEX	0,8	1,6	€/kg
Grey hydrogen production - CAPEX	0,4	0,4	€/kg
Grey hydrogen production - total costs	1,2	2	€/kg
LCOH	1,5	3	€/kg
CO2 emitted from SMR	9	9	kg/kg H2
Grey hydrogen production - CO2 costs	0,3	1,0	€/t
ETS CO2 price	**33**	**111**	**€/t**

7 The Presentation of Results

The presentation of results summarises the consequences of each chapter. A massive deployment of the large-scale renewables began ten years ago. It lasted only three years when approximately 450 MW renewables, mainly the photovoltaic power plants, have been installed. The Slovak TSO has noted potential risks in the security of the transmission system. The TSO has recommended not to connect the new RES over 10 kW based on its internal analysis.

As a result, the development of the variable RES was stopped, which most likely causes the failure of meeting the binding renewable targets specified for 2020. Today approximately 650 MW of RES generates the green electricity for Slovakia. From this power, just five wind turbines are in operation. On the other hand, more than 500 MW of PV plants operates using the feed-in tariffs at the utility-scale. The Slovak Republic has set the national energy and climate plan to increase the share of the renewable electricity sources in domestic consumption from 14% to 19,2%. In its NECP, Slovakia estimates the installed power in 2030 would rise in the wind to 0,5 GW, and the wind to, and in solar PV plants 1,2 GW, which will produce 2,3 TWh (1 TWh wind and 1,13 TWh) of variable renewable electricity in 2030. The national support of RES left FIT subsidies in 2019 and applied more market oriented FIP or Action system for large variable RES and local sources.

Hydrogen as the versatile carbon-free energy carrier can interconnect the energy sector with industry and transport. It can store a vast amount of energy seasonally. It can act as a buffer for the energy system and use the existing gas infrastructure for distribution. It can decarbonise the transport sector and the heating of buildings. It serves as a CO_2-free feedstock in the refinery, chemical industry or during steelmaking. It can offer a high gradient heat for the cement industry. The drawback, such as the relatively high capital expenditures of hydrogen technologies, a missing hydrogen value chain and both technical and political barriers, do not allow their broader penetration to the market.

When hydrogen transport becomes a stronger governmental priority, FCEVs (cars, buses, trucks or trains) will consume 12000 tons of hydrogen in 2030. When hydrogen is produced by water electrolysis, 0,6 TWh of renewable power is needed. Currently, the Slovak industrial sector consumes 0,2 Mt of fossil-based hydrogen annually. Slovnaft refinery and Duslo ammonia plant produce and use hydrogen from the natural gas and emitted 1,95 Mt of CO_2 in 2019. The replacement of all grey hydrogen by the green one would require 10 TW of the renewable power which is a third of the current Slovak power generation. Therefore, the hydrogen replacement in the industrial sector is a long-term task. Moreover, if the steelmaker USS Košice changes its carbon furnace steelmaking route to the direct reduction of iron by using the hydrogen, Slovakia will not cover the whole hydrogen need from a local resource. Slovakia has a significant potential to decarbonise the second densest grid in the EU by hydrogen. By injecting hydrogen to the gas grid up to 2% concentration, the gas grid does not need any adjustment on gas infrastructure and appliances.

The case study appraises a 150 MW wind farm directly supplying the 50 MW PEM electrolyser by the renewable power in the south-west Slovakia. The study calculates with the 20 years investment horizon and 7,5 WACC. Both technologies create the Power-to-Hydrogen plant. The higher capacity factor of the electrolyser is the reason why to overpower the wind farm. In this case a triple overpowering means 1,6 times higher capacity factor for the electrolyser as Figure 27 illustrates.

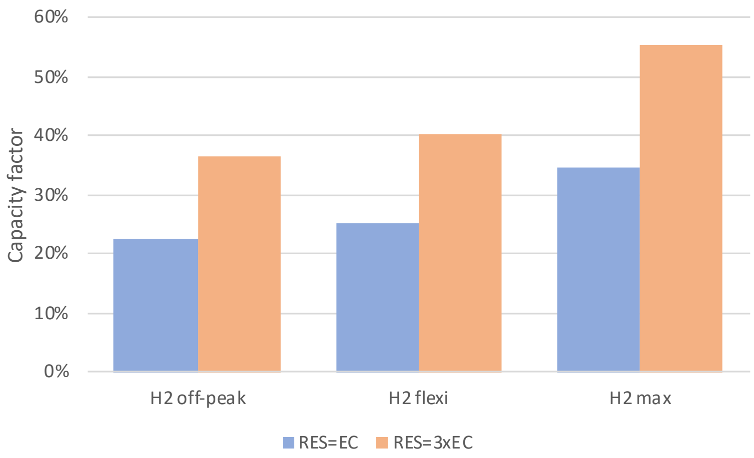

Figure 27: Capacity factor of electrolyser influenced by overpowering strategy (own chart)

The excessed power from the wind farm is delivered to the grid, however, no grid power is used in the electrolyser, except for the balancing power to provide the ancillary services for the transmission grid. The Case study prefers the wind power, rather than PV due to the higher capacity factor and the lower levelised cost of energy in the conditions of Slovakia. The new 6,2 MW low wind turbines were chosen to generate the green power at the average wind speed of 6,4 m/s. The rotor with a diameter of 170 m will harvest wind energy at the hub eight of 135m. Each turbine can generate almost 18 GWh a year. The 24 wind turbines, with the nominal power 6,2 MW each, can generate together more than 450 GWh renewable power a year. The direct input data from the Danish wind farm developer Eurowind energy S/A show that the specific costs of the wind technology drop down to 0,864 M€/1MW. The total CAPEX of 158,3 M€ and the annual OPEX of 2,2 M€ push the LCOE down to 41,69 €/MWh.

The business case evaluates three supply-demand scenarios. The case study examines the RES to EC supply-demand relationship in 3 scenarios. In the first scenario, **H2 off-peak**, the electrolyser uses only the off-peak electricity, when the demand for electricity in the country is relatively low. It means during the working days it works at nights from 8 pm to 8 am, and at the weekends and on holidays it works for 24 hours. In the second scenario, the **H2 flexi**, the electrolyser uses the electricity like H2 off-peak and also when a spot market price drops under the level of the agreed EC price. In the third scenario, **H2 max**, the electrolyser uses the electricity from RES primarily without any limits, 24 hours a day annually.

The oxygen market in Slovakia is limited. Oxygen as a by-product of the electrolysis can be sold for the industrial purposes for the price of 25 €/ton providing at least half of the production can be sold with a yield from 0,29 to 0,45 Mt annually depending on the scenario. About 37% of the renewable power is transformed to the waste heat in the electrolyser due to the 63% conversion efficiency. From the waste heat, ca a half can be captured and used for the heating of 3 ha of the neighbouring greenhouse farm. The earnings from sale of heat are insignificant compared to the sale of hydrogen. The earnings from the provision of the ancillary services are very limited too. The electrolyser does not meet the technical conditions to offer some valuable FRR or FCR services. Therefore, only the increasement of the load can be sold to TSO for the price of 3 €/MWh with the dedicated capacity of 10 MW. This increases the incomes by 0,26 M€ annually. Figure 28 shows the sale structure in each scenario.

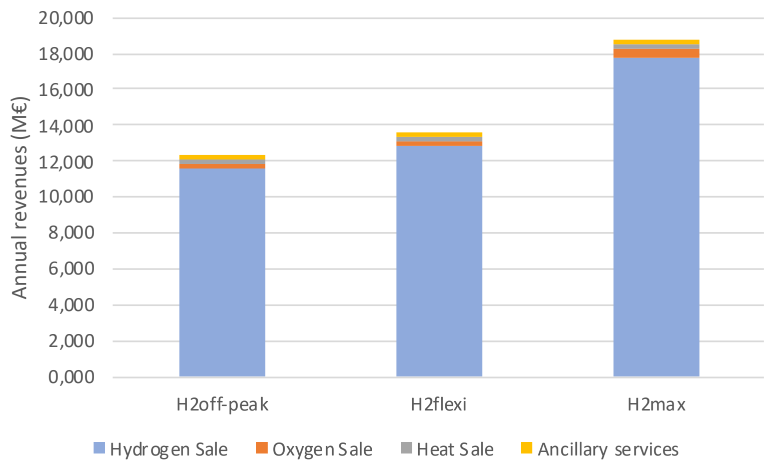

Figure 28: The Revenue Structure from the Electrolysis (own chart)

All the EC's by-products can decrease the LOHC, however, in this case study their negligible share of 7% from the total incomes could not help to decease LCOH under 4,00 €/kWh.

As Figure 29 and Table 23 present, **the LCOH is higher than the hypothetic € 4,00 /kg H_2. Subsequently, NPV turns to negative values that indicate a loss at the**

end of the investment horizon. The calculation of the dynamic investment analyses of the H2 max scenario shows Appendix 3.

Table 23: LCOH & NPV (own table)

	H2off-peak	H2flexi	H2max
LCOH (€/kg H2)	4,84	4,71	4,17
NPV (M€)	-24,83	-23,12	-7,60

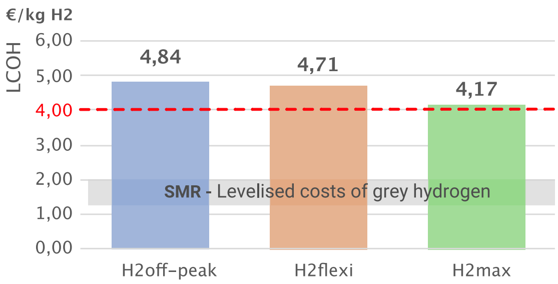

Figure 29: The Levelised Cost of Hydrogen (own chart)

The original assumptions counted with a more significant share of the incomes from the ancillary services on the total incomes, however, after the discussion with SEPS, the national TSO, EC does not fulfil the strict conditions for delivering the rewarding services today, such as FCR of FRR. Therefore, in this calculation, the grid services participate by 2% on the total incomes, while by 1% on the sale of oxygen and heat. By 2024, the national TSO must implement the EU rules to the grid services, FCR and FRR could be applied referring the EC. Then the total revenues can grow by a third, and LCOH can be reduced to 3,50 €/kg.

The sensitivity analysis illustrates how the change of the critical input parameters influences the LCOH value. The analysis was performed in each scenario with the identical inputs of CAPEX, EC power price – the energy cost, FLH – the EC utilisation and WACC – the capital costs. Figure 30 clearly shows that the utilisation of the electrolyser is a crucial factor for lowering LCOH.

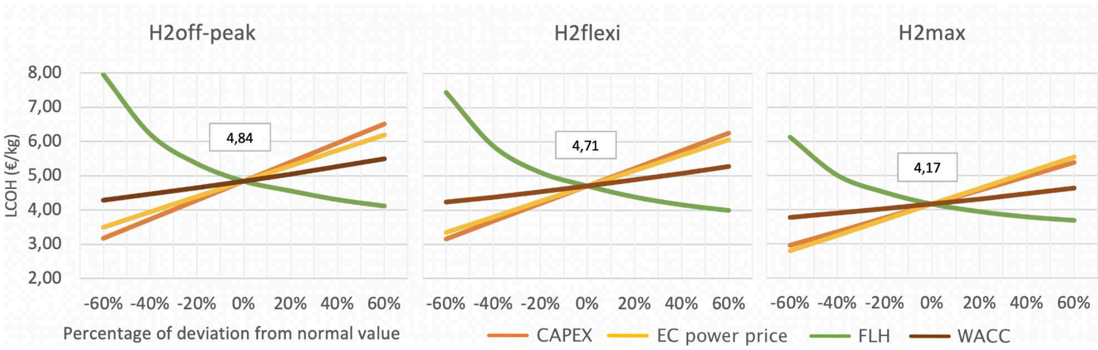

Figure 30: The Sensitivity Analysis of the Levelised Costs of Hydrogen regarding the CAPEX, EC Electricity Price, FLH, and WACC (own charts)

The most important outcome of this master thesis is that the higher utilisation of EC indicates the lower LCOE to compete the grey hydrogen, as Figure 31 shows.

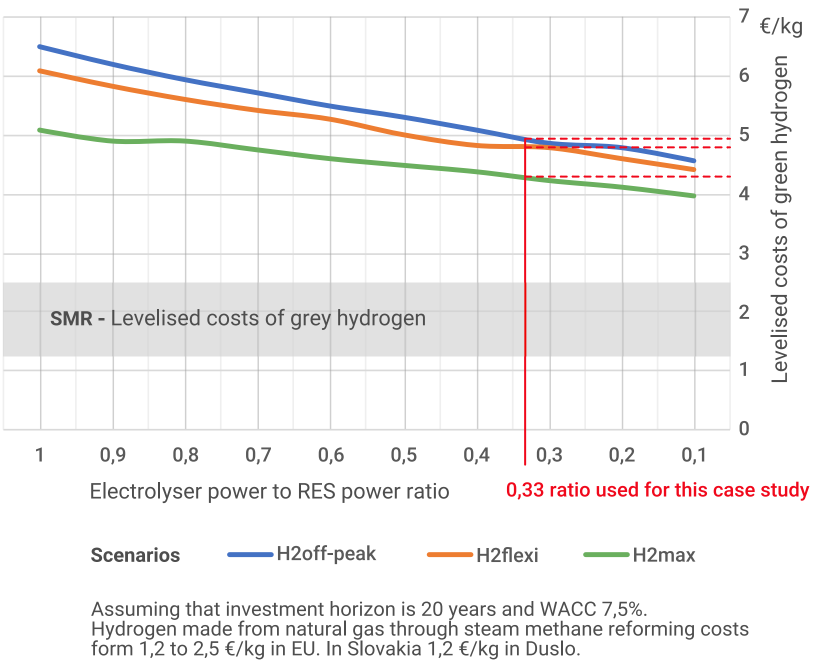

Figure 31: The Sensitivity Analysis of the Levelised Costs of Hydrogen concerning the Overpowering Share (own chart)

There are two ways of increasing the capacity factor of EC additionally. Alternatively, to add more RES installing power or to use the power from the grid. The second possibility brings a question: How green is the power from the grid when the national TSO must increase the interconnectivity, and more power with the higher carbon footprint will flow to Slovakia from Poland and the Czech Republic?

Furthermore, the real opportunity for the LCOH reduction means a reduction of CAPEX. The EU has recently announced the support of installing the 6 GW electrolysers by 2024 within the EU. Potential investors can apply for a financial support, e.g. from the Innovation Fund or joining the scheme of the Important Project of Common European Interest (IPCEI).

8 The Conclusions and Recommendations

There are several barriers in Slovakia to overcome. This master thesis explains how hydrogen can help to make the transport sector carbon-neutral in the mid-term horizon. Providing Slovakia starts using the clean hydrogen, it will have a carbon-neutral economy by 2050. A significant opportunity of the implementation of the sustainable hydrogen value chain is the reduction of the costs of the hydrogen technologies. It can be achieved by a scaling-up of the hydrogen components. This master thesis confirms that a Power-to-Hydrogen plant can support the power grid resilience by offering the EC capacity to provide the ancillary services in the H2 off-peak and the H2 flexi scenario. Using electricity from the grid, when the preferred RES is not able to deliver enough power to the electrolyser, can enable the optimal utilisation of the electrolysers. In praxis, removing the fees and taxes from the price of electricity loading from the grid is the significant opportunity for the large-scale hydrogen production via water electrolysis. The Power-to-Hydrogen technologies have the potential to accelerate the RES deployment in Slovakia and help meet the targets agreed in the National Energy & Climate Plan.

The results of the case study show that the wind farm is profitable without the needs of any subsidies even if it sells the excessed electricity for the market prices. Moreover, the fixed purchase price, secured by purchase contract with the electrolyser operator, avoids more and more often curtailments. The electrolyser can offer this minimal price due to the fixed electricity purchase contract. The electrolyser is not able to produce hydrogen under the price of 4 €/kg in any of the 3 assessed scenarios today. The next findings show that the capability of the electrolyser to provide the more valued FCR and FRR ancillary services to TSO requires detailed research. The profitable operation without any side earnings needs a CAPEX subsidy for the electrolyser in the amount of 42% for H2 off-peak, 39% for H2 flexi and 23% for H2 max scenario to match the 4 €/kg clean hydrogen price. The operational model of H2 max scenario is the most beneficial from the economic point of view thanks to the highest capacity factor of the operation. On the other hand, H2 flexi scenario proves the better support of the integration of RES due to preferred electricity supply to the grid when it is needed during the high demand in the country.

There are several barriers in Slovakia to overcome for the successful implementation and operation of a Power-to-Hydrogen plant. One of the substantial legislative barriers is the limit of 500 kW per a “Local Source”. The “Local Source” means a local renewable electricity source for the own consumption of the owner of the source. Here the current maximum capacity of 500 kW per a single source limits the deployment of the large-scale combined power and hydrogen plants. An unlimited local source allows supplying EC by RES without any taxes and fees. The second barrier, “the G-component”, is a distributive fee that must be reduced or removed. Today, a 1 MW RES connected to the grid is obliged to pay a fee in the amount of 1695,12 € per each installed MW monthly to a distribution system operator. In case of a 150 MW wind farm, this would increase the costs by 3,05 M€ annually and $LGRC_{EL}$ by 7,76 €/MWh. The third and the most significant barrier is the lack of hydrogen consumers in the transport sector, in other words, the uncomplete hydrogen value chain. This means that the complete value chain must be built at once.

Today, grey hydrogen is 2-3 times cheaper than the green one. If in 2030 three assumptions are met that the production price of green hydrogen will decrease to € 3 per kg, the price of natural gas will double, and the price of CO_2 ETS will increase above € 111 per a ton then the production prices of green and grey hydrogen achieve the parity. From this moment, the renewable Power-to-Hydrogen plants will no longer need financial support and will become market competitive.

When the decision-makers remove the main barriers, the Power-to-Hydrogen plant deployment can begin. However, the future deployment of the Power-to-Hydrogen plants must respect many criteria and limits referring the location of a Power-to-Hydrogen plant.

The placement criteria of the Power-to-Hydrogen plants are as follows:

- a stable windy area,
- a flatland or a top of the hill,
- a location with no environmental limits,
- a location off the scenic landscapes,
- a location off the urban areas,
- in case of a PV plant – off the arable lands,
- in case of a wind farm – off the airspace corridors and the bird bio corridors.

The locations of a Power-to-Hydrogen plant should be close to a transformer station with the required free capacity for the connection, consumers of hydrogen or a gas grid. The suitable areas that most likely meet the criteria mentioned above are showed on the map in Figure 32.

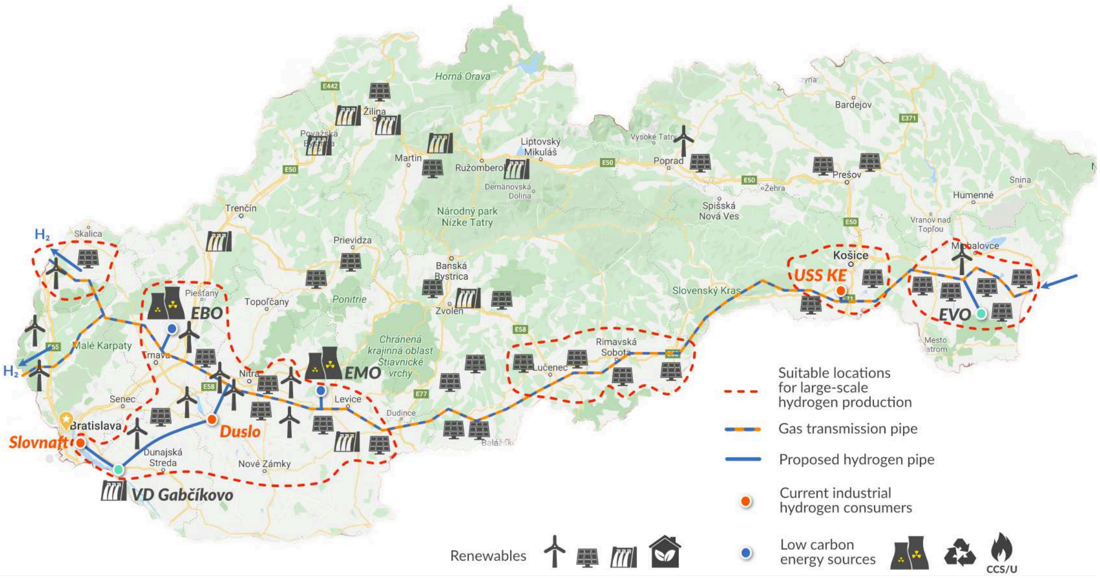

Figure 32: The Suitable Areas for the Large-scale Hydrogen Production in the Long-term Horizon. Source: (NVAS, 2020, unpublished)

This master thesis has the ambition to serve as a background for the Slovak government and the key business decision-makers, when considering how to deploy the Power-to-Hydrogen plants in Slovakia, in order to achieve the carbon neutral target within the energy, industry and transport sector.

Abbreviations and Acronyms

BEV	battery electric vehicle
BoP	balance of plant
CAPEX	capital expenditure
CO_2eq	carbon oxide equivalent
CP	capacity factor
EC	electrolyser
EU	European Union
FCEV	fuel cell electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCR	frequency containment reserve
FIP	feed-in-premium
FIT	feed-in-tariff
FLH	full load hours
FRR	frequency restoration reserves
HEV	hybrid electric vehicles
HHV	higher heating value
ICE	internal combustion engine
LCOE	levelised cost of energy
LCOH	levelised cost of hydrogen
$LGRC_{EL}$	long run generation costs of electricity
LHV	lower heating value
MEA	membrane electrodes assembly
mFRR	manual Frequency Restoration Reserve
NECP	national climate and energy plan
NPV	net present value
O&M	operation and maintenance
OKTE	Organiser of the short-term electricity market
OPEX	operational expenditure
PEM	proton exchange membrane
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
R&D	research development and demonstration
RE	renewable
RES	renewable electricity source
RONI	Regulatory Office for Network Industries
SMR	steam methane reforming
SR	Slovak Republic
T&D	transmission and distribution
TSO	transmission system operator
WACC	weighted average cost of capital

Bibliography

Ajanovic Amela and Haas Reinhard (2018): Economic prospects and policy framework for hydrogen as fuel in the transport sector, *Energy Policy*, 123, pp. 280–288. doi: https://doi.org/10.1016/j.enpol.2018.08.063.

Bertuccioli Luca / Chan Alvin / Hart David / Lehner Franz / Madden Ben and Standen Eleanor (2014): Study on development of water electrolysis in the EU, pp. 65–67. Available at: https://www.fch.europa.eu/sites/default/files/FCHJUElectrolysisStudy_FullReport (ID 199214).pdf (Retrieved on: September 9, 2020).

Christensen Adam (2020): Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe, pp. 18–20. Available at: https://theicct.org/publications/assessment-hydrogen-production-costs-electrolysis-united-states-and-europe (Retrieved on: October 11, 2020).

DTU Wind Energy (2020): *Global Wind Atlas*. Available at: https://globalwindatlas.info/ (Retrieved on: September 27, 2020).

ENTSO-E (2020): *Balancing and Ancillary Services Markets*. Available at: https://www.entsoe.eu/about/market/#balancing-and-ancillary-services-markets (Retrieved on: September 29, 2020).

EUR-Lex (2017): *Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.220.01.0001.01.ENG&toc=OJ:L:2017:220:TOC#d1e394-1-1 (Retrieved on: September 29, 2020).

European Commission (2020): Verified Emissions for 2019. Available at: https://ec.europa.eu/clima/sites/clima/files/ets/registry/docs/verified_emissions_2019.xlsx (Retrieved on: September 14, 2020).

FCH 2 JU (2019): *A sustainable pathway for the European energy transition: Hydrogen roadmap Europe.* doi: 10.2843/249013.

FCH 2 JU (2020): FCHO Reports: Chapter 2 Hydrogen molecule market, p. 3. Available at: https://www.fchobservatory.eu/sites/default/files/reports/Chapter_2_Hydrogen_Molecule_Market_070920.pdf (Retrieved on: September 17, 2020).

FCH JU (2020): *Slovakia: Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*. Available at: https://www.fch.europa.eu/sites/default/files/file_attach/Brochure FCH Slovakia (ID 9474177).pdf (Retrieved on: September 27, 2020).

Heat Roadmap Europe 4 (2017): Heating and Cooling: Fact and Figures, *Heat Roadmap Europe*, pp. 4, 5. Available at: https://hre.aau.dk/wp-content/uploads/2018/09/29882_Brochure_Heating-and-Cooling_web-1-2.pdf.

Hydrogen Council (2017): How hydrogen empowers the energy transition, pp. 1–11. Available at: http://hydrogencouncil.com/study-how-hydrogen-empowers/ (Retrieved on: September 26, 2020).

Hydrogen Europe (2019): *Projects — Hydrogen for Climate Action*. Available at: https://www.hydrogen4climateaction.eu/projects (Retrieved on: September 25, 2020).

Hydrogen Europe (2020a): *HYDROGEN EUROPE: CLEAN HYDROGEN MONITOR 2020 | Hydrogen*. Available at: https://hydrogeneurope.eu/node/1691 (Retrieved on: October 10, 2020).

Hydrogen Europe (2020b): *Hydrogen Production | Hydrogen*. Available at: https://hydrogeneurope.eu/hydrogen-production-0 (Retrieved on: September 28, 2020).

IEA (2018): Global Energy & CO2 Status Report, *The latest trends in energy and emissions in 2018*. Paris: IEA, pp. 11, 12. Available at: https://www.iea.org/geco/electricity/.

IEA (2019): Hydrogen: Seizing today's opportunities, *The Future of Hydrogen*. doi: 10.1787/1e0514c4-en.

IEA (2020): *Tracking Industry 2020*. Available at: https://www.iea.org/reports/tracking-industry-2020 (Retrieved on: October 27, 2020).

ILK Dresden (2020): *Hydrogen and methane testing field at the ILK*. Available at: https://www.ilkdresden.de/en/service/research-and-development/project/hydrogen-test-area-at-ilk-dresden/ (Retrieved on: September 26, 2020).

International Hydropower Association (2018): *2018 Hydropower Status Report*, *2018 Hydropower Status Report*. Available at: https://www.hydropower.org/publications/2018-hydropower-status-report (Retrieved on: August 12, 2020).

IRENA (2020): Renewable Power Generation Costs in 2019. Abu Dhabi, pp. 11, 12. Available at: /publications/2020/Jun/Renewable-Power-Costs-in-2019 (Retrieved on: September 30, 2020).

ITM Power (2020): *HGas10MW | Largest Electrolyser System*. Available at: https://www.itm-power.com/images/Products/HGasXMW.pdf (Retrieved on: October 10, 2020).

Lappalainen Mikko (2019): *Techno-economic feasibility of hydrogen production via polymer membrane electrolyte electrolysis for future power-to-x systems*. Tampere University. Available at: https://trepo.tuni.fi/bitstream/handle/123456789/27224/Lappalainen.pdf?sequence=4&isAllowed=y (Retrieved on: September 5, 2020).

Ministry of Economy of the Slovak Republic (2019a): Integrated National Energy and Climate Plan for 2021 to 2030. Bratislava, pp. 3–47. Available at: https://ec.europa.eu/energy/sites/ener/files/sk_final_necp_main_en.pdf (Retrieved on: September 14, 2020).

Ministry of Economy of the Slovak Republic (2019b): Správa o pokroku v presadzovaní a využívaní energie z obnoviteľných zdrojov energie Slovenská republika. Available at: https://www.mhsr.sk/uploads/files/qNPBXtHE.pdf (Retrieved on: October 11, 2020).

Morthorst P. E. and Kitzing L. (2016): 2 - Economics of building and operating offshore wind farms, in Ng, Chong and Ran, Li B. T. Offshore Wind Farms (eds.). Woodhead Publishing, pp. 9–27. doi: https://doi.org/10.1016/B978-0-08-100779-2.00002-7.

Nuffel Luc van / Dedecca João Gorenstein / Yearwood Jessica / Smit Tycho / Bünger Ulrich / Altmann Matthias / Fischer Christian / Michalski Jan / Raksha Tetyana / Zerhusen Jan and Vita Alessia De (2019): *Impact of the use of the biomethane and hydrogen potential on trans-European infrastructure*. Luxembourg. doi: 10.2833/077257.

OECD/IEA (2015): Technology Roadmap, Hydrogen and Fuel Cells. IEA, pp. 10–20. Available at: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf.

OECD/IEA (2017): Tracking Clean Energy Progress 2017. Paris: IEA, p. 13. Available at: https://www.iea.org/reports/tracking-clean-energy-progress-2017.

OKTE (2020): *Spot market*. Available at: https://www.okte.sk/sk/kratkodoby-trh/zverejnenie-udajov/rocna-sprava-o-dt/#eyear=2019&iyear=2019&tab=2 (Retrieved on: October 8, 2020).

Ordin Paul M. (1997): Safety standard for hydgogen and hydrogen systems. Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation, *National Aeronautics and Space Administration*. doi: 10.1016/j.trac.2006.06.009.

Palzer A. and Henning H. M. (2014): A future German energy systen with a dominating contribution from renewable energies: A holistic model based on hourly simulation, *Energy technology*, 2(Nr.1), pp. 13–28.

Railways of the Slovak Republic (2020): *Annual Report 2019*. Bratislava: ZSSK. Available at: https://www.zssk.sk/wp-content/uploads/2020/08/Vyrocna-sprava_SK_2019_FINAL_WEB.pdf (Retrieved on: September 9, 2020).

Regulatory Office for Network Industries (2020): *Annual Report 2019*. Available at: https://www.sepsas.sk/Dokumenty/VyrocneSpravy/2020/SEPS-VS2019.pdf (Retrieved on: September 14, 2020).

van der Roest Els / Snip Laura / Fens Theo and van Wijk Ad (2020): Introducing Power-to-H3: Combining renewable electricity with heat, water and hydrogen production and storage in a neighbourhood, *Applied Energy*, 257, p. 114024. doi: 10.1016/j.apenergy.2019.114024.

Schwaiger Robert (2016): *Electricity generation with renewables in Austria; An economic analysis of biomass combustion CHP, photovoltaic, small hydro-and wind power*. TU-Wien.

SEPS (2012): *Conclusions of the study "Assessment of the impact of renewable electricity sources operated in the Slovak Republic on the Slovak electricity system."* Available at: https://www.sepsas.sk/informacia2012_11_30.asp?Kod=517&Nadrad=612 (Retrieved on: September 25, 2020).

Shell (2017): *Energy of the future? - Sustainable mobility through fuel cells and H2*, *Shell Deutschland Oil GmbH*. Hamburg. Available at: www.shell.de (Retrieved on: October 29, 2018).

SlovLex (2020): *Act Nr. 309/2009 Z.z. - Zákon o podpore obnoviteľných zdroj... - SLOV-LEX*. Available at: https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2009/309/20200101 (Retrieved on: September 15, 2020).

Smolinka T. / Rau S. and Hebling C. (2010): Polymer electrolyte membrane (PEM) water electrolysis, *Hydrogen and fuel cells*, pp. 271–289.

Torres Alvarado Luis Hernandez (2019): *Cost approach for Hydrogen production by Electrolysis (PEM Technology).* Available at: https://www.linkedin.com/pulse/cost-approach-hydrogen-production-electrolysis-pem-hernandez-torres/ (Retrieved on: October 10, 2020).

tuochIT (2020): *Messer Tatragas sa pripravuje na zvýšenú spotrebu kyslíka. O pomoc žiada aj zákazníkov | TOUCHIT*. Available at: https://touchit.sk/messer-tatragas-sa-pripravuje-na-zvysenu-spotrebu-kyslika-o-pomoc-ziada-aj-zakaznikov/287904 (Retrieved on: September 29, 2020).

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Appendices

Appendix 1: Definition of the origin of hydrogen

Hydrogen categories used in this work has been derived from the *Hydrogen strategy for a climate-neutral Europe*. Definitions are as follows:

Electricity-based hydrogen refers to hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), regardless of the electricity source. The full life-cycle greenhouse gas emissions of the production of electricity-based hydrogen depend on how the electricity is produced.

Renewable hydrogen (known as green hydrogen) is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources. The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero. Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.

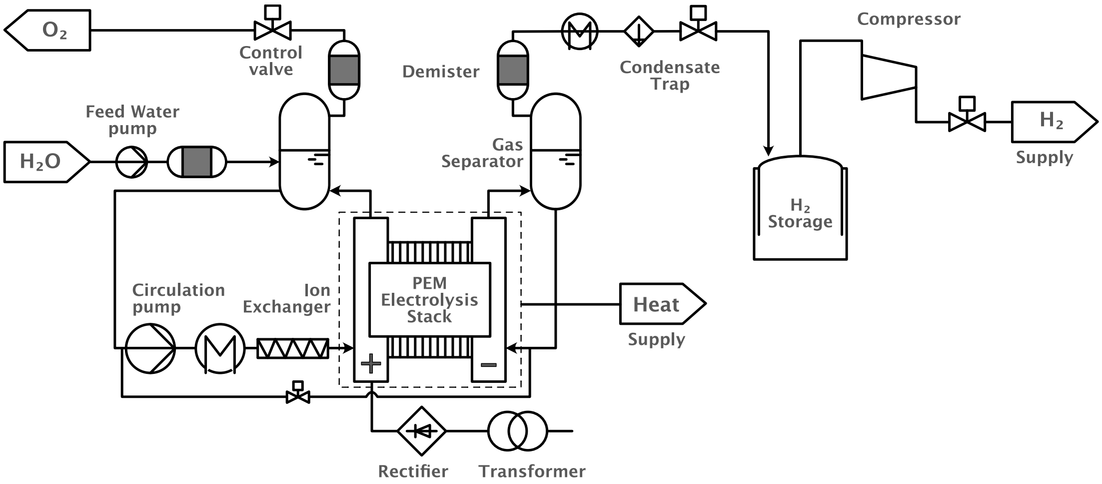
Clean hydrogen refers to renewable hydrogen.

Fossil-based hydrogen (known as grey hydrogen) refers to hydrogen produced through a variety of processes using fossil fuels as feedstock, mainly the reforming of natural gas or the gasification of coal. This represents the bulk of hydrogen produced today. The life-cycle greenhouse gas emissions of the production of fossil-based hydrogen are high.

Fossil-based hydrogen with carbon capture (known as blue hydrogen) is a subpart of fossil-based hydrogen, but where greenhouse gases emitted as part of the hydrogen production process are captured. The greenhouse gas emissions of the production of fossil-based hydrogen with carbon capture or pyrolysis are lower than for fossil-fuel based hydrogen, but the variable effectiveness of greenhouse gas capture (maximum 90%) needs to be taken into account.

Low-carbon hydrogen (known as blue hydrogen) encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production.

Appendix 2: Layout of a PEM electrolysis system



Source: (Smolinka *et al.*, 2010)

Appendix 3: Dynamic Investment Analysis – 50 MW Electrolyser

(H2 max scenario in M€)

Year	CASH FLOW		REVENUES				COSTS					
	Discounted	Nominal	Hydrogen Sale	Oxygen Sale	Heat Sale	Ancillary services	O&M with escalation	Electricity	Water	Investment & Replacement	Total Nominal	Total Discounted
0	-61,98	-61,98								61,98	61,98	61,98
1	4,62	4,97	17,81	0,45	0,29	0,26	4,05	9,73	0,05	0,00	13,83	12,87
2	4,17	4,82	17,81	0,45	0,29	0,26	4,13	9,80	0,05	0,00	13,98	12,10
3	3,76	4,67	17,81	0,45	0,29	0,26	4,21	9,87	0,06	0,00	14,13	11,37
4	3,38	4,52	17,81	0,45	0,29	0,26	4,29	9,93	0,06	0,00	14,28	10,69
5	3,04	4,37	17,81	0,45	0,29	0,26	4,38	10,00	0,06	0,00	14,43	10,05
6	2,73	4,21	17,81	0,45	0,29	0,26	4,47	10,06	0,06	0,00	14,59	9,45
7	2,45	4,06	17,81	0,45	0,29	0,26	4,56	10,13	0,06	0,00	14,74	8,89
8	2,19	3,90	17,81	0,45	0,29	0,26	4,65	10,19	0,06	0,00	14,90	8,36
9	1,95	3,74	17,81	0,45	0,29	0,26	4,74	10,26	0,06	0,00	15,06	7,86
10	0,15	0,32	17,81	0,45	0,29	0,26	4,84	10,32	0,06	3,26	18,48	8,97
11	1,54	3,41	17,81	0,45	0,29	0,26	4,93	10,39	0,06	0,00	15,39	6,94
12	1,36	3,25	17,81	0,45	0,29	0,26	5,03	10,46	0,07	0,00	15,55	6,53
13	1,20	3,08	17,81	0,45	0,29	0,26	5,13	10,52	0,07	0,00	15,72	6,14
14	-2,14	-5,89	17,81	0,45	0,29	0,26	5,23	9,39	0,07	10,00	24,69	8,97
15	1,33	3,94	17,81	0,45	0,29	0,26	5,34	9,45	0,07	0,00	14,86	5,02
16	1,18	3,77	17,81	0,45	0,29	0,26	5,45	9,52	0,07	0,00	15,03	4,73
17	1,05	3,59	17,81	0,45	0,29	0,26	5,55	9,58	0,07	0,00	15,21	4,45
18	0,93	3,41	17,81	0,45	0,29	0,26	5,67	9,65	0,07	0,00	15,39	4,19
19	0,82	3,23	17,81	0,45	0,29	0,26	5,78	9,71	0,08	0,00	15,57	3,94
20	0,72	3,05	17,81	0,45	0,29	0,26	5,89	9,78	0,08	0,00	15,75	3,71
SUM	**-25,53**	**2,45**	**356,14**	**8,90**	**5,81**	**5,19**	**98,32**	**198,74**	**1,29**	**75,24**	**373,59**	**217,21**
											Annuity of costs	**20,31**

Capacity Recovery Factor [CRF]

$$CRF = \frac{r \cdot (1+r)^T}{(1+r)^T - 1}$$

CRF = 0,098

Net present Value (NPV)

$$NPV = \sum_{t-1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

T - investment horizon [yr]
t - year-count
Ct - Cash flow in year t [€]
r - Discount rate / cost of capital
C_0 - Initial investment [€]

NPV = -25,53 M€

Annuity

$$= NPV \cdot CRF$$

$\alpha =$ -2,50 M€

Long Run Generation Costs

$$\text{LRGC} = \left(\frac{Annuity\ of\ costs}{Annual\ hydrogen\ production} \right)$$

4,56 €/MWh $= \left(\frac{20{,}312}{4{,}452} \right)$

Appendix 4: Dynamic Investment Analysis – Wind Farm 150 MW (in M€)

(H2 max scenario in M€)

Year	CASH FLOW		YIELDS	COSTS			
	Discounted	Nominal	Electricity Sale	O&M with escalation	Investment & Replacement	Nominal	Discounted
-1		-47,50			47,50	47,50	
0	-159,27	-110,83			110,83	110,83	159,27
1	15,36	16,51	18,84	2,32		2,32	2,16
2	14,25	16,47	18,84	2,37		2,37	2,05
3	13,22	16,42	18,84	2,42		2,42	1,94
4	12,26	16,37	18,84	2,46		2,46	1,85
5	11,37	16,32	18,84	2,51		2,51	1,75
6	10,54	16,27	18,84	2,56		2,56	1,66
7	9,78	16,22	18,84	2,62		2,62	1,58
8	9,07	16,17	18,84	2,67		2,67	1,50
9	8,41	16,12	18,84	2,72		2,72	1,42
10	6,26	12,89	18,84	2,78	3,17	5,94	2,88
11	7,22	16,01	18,84	2,83		2,83	1,28
12	3,37	8,03	18,84	2,89	7,92	10,80	4,54
13	6,21	15,89	18,84	2,95		2,95	1,15
14	5,75	15,83	18,84	3,00		3,00	1,09
15	5,33	15,77	18,84	3,06		3,06	1,04
16	4,94	15,71	18,84	3,13		3,13	0,98
17	4,58	15,65	18,84	3,19		3,19	0,93
18	4,24	15,58	18,84	3,25		3,25	0,88
19	3,93	15,52	18,84	3,32		3,32	0,84
20	3,64	15,45	18,84	3,38		3,38	0,80
SUM	**0,44**	**150,90**	**376,73**	**56,42**	**169,41**	**225,83**	**191,58**

Annuity of costs **18,79**

191,58

Capacity Recovery Factor [CRFT]

$$CRF = \frac{r \cdot (1+r)^T}{(1+r)^T - 1}$$

CRF = 0,098

Net present Value (NPV)

T - investment horizon [y]
t - year-count
Ct - Cash flow in year t [€]
r - Discount rate / cost of capital
C_0 - Initial investment [€]

$$NPV = \sum_{t-1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

NPV = 0,444 mil. EUR

Annuity

$$= NPV \cdot CRF$$

$\alpha =$ 0,044 mil. EUR

Long Run Generation Costs **LCOE**

$$\text{LRGC} = \left(\frac{Annuity\ of\ costs}{Yerly\ electricity\ production} \right)$$

41,69 €/MWh $= \left(\frac{18\,793}{451} \right)$