

Master thesis

The potential role of Power-to-Gas in the Russian-European energy system

by
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Sincerely,

Veronika Lenivova

Declaration of Origin

I hereby certify that the master thesis on the topic,

“The potential role of Power-to-Gas in the Russian-European energy system”

submitted under my name is the original research work, has been written independently and represents my own visions. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions. Any source of assistance or the idea from other works have been appropriately acknowledged.

Additionally, I assure that the master thesis has not been a part of any examination process and has not been published.

Veronika Lenivova

Cottbus, 8th June 2020

Abstract

The modern world is currently facing the energy revolution due to the decarbonisation challenges, promoted by the United Nations Framework Convention on Climate Change (UNFCCC). The well-established fossil fuel energy sources are being pushed from their leading market positions by renewable energy. European governments are some of the first to take decisive action towards decarbonisation and have already started reforming their economic sectors. New questions arising from such changes are influencing the role of Russia in supplying energy to the European market. The development of a market for renewable gas, especially renewable hydrogen in Europe, could potentially, in a long-term scenario up to 2050, be an option for Russia to help maintain demand and remain in the role as a main exporter.

The focus of this master thesis is put on the assessment of the current state of readiness of Russian and European energy systems for integration of Power-to-Gas (PtG) systems and for development of a carbon-free hydrogen market. German internal green hydrogen production capacity cannot meet the approximate demand in 2030 and 2050. However, the presence of the unutilised power capacity from Russian nuclear and hydro power plants opens a new opportunity to generate economically attractive hydrogen in large volumes via electrolysis with low electricity costs and zero carbon dioxide footprint.

In this thesis different supply chains for hydrogen export (Russia-Germany) are constructed and, as a result, the levelised costs of hydrogen (LCOH) are calculated and analysed. Hydrogen produced in Russia and transported to Germany via maritime shipment shows that it can already be competitive to the domestically produced green hydrogen in Germany. The main compartment of the LCOH is the electricity expenditure, which the current Russian industrial tariffs can reach up to 90% of the total costs. Further reductions of the electricity price for PtG systems are recommended in order to achieve lower results for the LCOH.

The outcome of this master thesis provides an overview on the current readiness of Russian and German hydrogen infrastructure and further recommendations on how it should be adapted. Finally a 2050 roadmap for the implementation of a hydrogen market in Russia and Germany is developed.

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List of Acronyms

Ammonia (NH ₃)	67	internal combustion engine (ICE).....	48
Anion Exchange Membrane (AEM).....	34	International Energy Agency (IEA)	5
battery-powered electric vehicles (BEV)	48	International Organisation for Standardisation (ISO)	74
billion cubic meters (bcm).....	11	kilowatt-hour (kwh).....	82
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Guarantees of Origin (GoO)	100	Operational expenditure (OPEX).....	87
higher heating value (HHV)	25	photovoltaics (PV)	4
hydrogen (H ₂)	1, 22	potassium hydroxide	

(KOH)	34	The Climate Action Regulation	
Power plants		(CAR)	16
(PP)	58	The International Panel on Climate Change	
Power-to-Gas (PtG)		(IPCC)	13
(PtG).....	1	The Organization of the Petroleum Exporting	
Primary Energy Consumption		(OPEC).....	5
(PEC)	36	the Paris Agreement	
Proton Exchange Membrane		(PA)	11
(PEM)	34	<i>the Renewable Energy Directive</i>	
Renewable energy		(RED II)	23
(RE)	4, 59	the steam methane reforming	
Renewable energy sources		(SMR)	26
(RES).....	59	transmission system operators	
Research and Development		(TSOs).....	45
(R&D)	35	Underground gas storage	
sodium hydroxide		(UGS).....	78
(NaOH).....	34	United Nations Framework Convention on	
Solid Oxide Electrolyser Cells		Climate Change	
(SOEC).....	34	(UNFCCC)	1
synthetic natural gas		water	
(SNG).....	32	(H ₂ O).....	22
Terawatt-hour		Combined heat and power type	
(TWh)	92	(CHP)	56

Introduction

In the era of decarbonisation, which is transitioning in new strategies and plans promoted by the United Nations Framework Convention on Climate Change (UNFCCC) are pushing the well-established conventional technologies to decline significantly or even disappear from leading market positions. European governments are some of the first to take decisive actions towards decarbonisation and have already started reforming their economic sectors. New questions arising from such changes are influencing the role of Russia in supplying energy to the European market. The development of a market for renewable gas in the European Union (EU) could potentially be an option for Russia to help maintain demand. Methane from municipal solid waste or biomass, syngas from gasification and hydrogen are possible alternatives for this transition. Hydrogen has an additional advantage due to its versatility. Besides its potential to be used in electricity generation, hydrogen (H_2) can be used in transportation, smart building (energy-efficiency), district heating and industrial applications (e.g. production of iron and steel, chemical and petrochemical industries and the food and pharmaceutical industries). Russia is the largest exporter of natural gas to Europe (in 2018 the share of consumption of natural gas in Europe from Russia reached 40.2%) (Eurostat, 2018) Thus, it is essential for Russia to foresee the changing structure of the European energy economy and be ready for quick adaptation to the new energy trends without losing its leading position.

In this master thesis the focus is put on the energy system of the European Union and Russia. The scope of the study is to assess the potential cooperation between these two large energy systems in terms of developing a carbon-free hydrogen market. The H_2 production method - Power-to-Gas (PtG) - is chosen in the master thesis due to its zero carbon footprint and its ability for sector-coupling and manifold applications. Considering the diverse and unclear structure of European energy system (especially in terms of energy policies and environmental boundaries), it was decided to focus only on Germany as the representative country from the EU. The reason lies in many factors, which are discussed in more details in Chapter 1.

Nevertheless, it is important to mention, that Germany, as an economic centre and industrial leader of the EU, has announced an ambitious energy transition pathway by eliminating nuclear

and coal (hard coal and lignite) capacities by 2038 and by increasing role of the variable renewable energy sources and renewable gases, such as hydrogen, in the energy mix. German government puts emphasis on the green hydrogen (produced from electricity, PtG) and promotes the country to become the global leader in the hydrogen economy by 2050. In order to reach ambitious targets of the German hydrogen demand, the potential low-carbon and green hydrogen exporters have to be established. Russia could become one of the leading hydrogen producers and suppliers in the world, due to its vast wind potential, beneficial geographic location to the strategic hydrogen markets and unutilised nuclear- and hydro- power plant capacities. Therefore, the aim of the master thesis is to analyse the chances of initiation of the hydrogen trade between Russia and Germany (The EU), to conduct technical-economic analysis of the hydrogen supply chain Russia-Germany and to determine the current challenges and obstacles, which are hindering development of the hydrogen economy.

Structure of the master thesis

Chapter 1 is designed as an introduction and general overview of the energy legislation and up-to-date renewable energy targets in Europe and in Germany particularly. The discussion starts with the comparison of current and future geopolitical positions between the European Union and Russia in the global energy game and continues with analysis of possible outcomes of the integrated decarbonisation policies on the fossil-fuel leading exporters. The role of green hydrogen as cross-sector energy carrier is introduced.

In *Chapter 2*, the focus is put on the potential role of PtG technology as a decarbonisation vector in the European Union. All possible spectrum of applications of PtG in energy, industry, transport and heating sectors are presented and discussed in detail, accompanied by relevant regulatory instruments and policy schemes. State of the art of current, future projects and level of readiness for the projects for commercialization are presented. In order to assess hydrogen demand in Europe and in Germany, different publications are presented and compared.

Chapter 3 is dedicated to the energy market in Russia and perspectives for integration of a new commodity - hydrogen. Three different ways of the production of green and yellow hydrogen are examined and compared in terms of the energy efficiency, total costs and deployment potential.

The idea is to generate hydrogen from electrolysis, supplied by nuclear, hydro or wind energy. Green hydrogen has significant environmental advantages when compared to other production routes (e.g. methane reforming/methane cracking). It can also be further upgraded to synthetic methane and other e-fuels. European countries with prevailing number of renewables installed are highly interested in the relatively cheap and CO₂ clean hydrogen for balancing of the intermittent renewable energy generation and replacing the phased-out capacities from coal and nuclear. Moreover, the transport routes from Russia to Germany and storage infrastructure, its challenges and possible solutions are covered. The chapter comprises the technical-economic analysis of different supply chains of hydrogen and resulted levelised cost of hydrogen (LCOH) are gathered for comparison and discussion.

The end goal of the master thesis is to form the roadmap for the introduction of a hydrogen market between Russia and Germany (Europe). The strategic analysis, perspectives and recommendations of the Russian-German-European Power-to-Gas system are gathered to understand the challenges that remain in *Chapter 4*.

Chapter 1. Project justification: The changes in The European Energy Policy and their possible implications for the demand of natural gas imports from Russia.

1.1 The Geopolitics and Energy Transition in European Union

With the increased amount of the renewable energy sources (especially wind turbines and solar power (photovoltaics (PV)) in the last couple of decades, the geopolitical global map based on the distributed conventional energy will be exposed to impending changes. The technical and geographical features of renewable energy (RE) are structurally different from the familiar and well-established fossil fuels. The nature of renewable energy sources is variable and intermittent, as it depends on the weather conditions (solar irradiation and speed of wind). Therefore, the energy generation should be backed up with the sufficient installed capacity reserve, in case the imbalances and forecast errors occur. Different, abundant energy storage systems could serve as an essential flexible addition to the unstable production of green electricity, by saving the surplus energy produced during the very windy and sunny days and utilizing it in the peak demand periods. Renewable energy technology, on the contrary to conventional, is small in capacity but comprised of many decentralised units. The components for renewable technology requires rare raw materials. Finally, the usage of renewable energy is mainly electrical and includes strict control conditions and technical constraints, as well as long-distance transmission losses.

The allocation of fossil fuel resources around the globe has shaped the energy geopolitics and determined the political relationships between countries since the 20th century. Thus, the main question arises how the change in energy mix towards more green sources of energy will influence the change in the strategic behavior of leading energy oligopolies, and what is crucial to understand, who will be the “winners” and “losers” of the energy transition game.

In the book “The Geopolitics of Renewables” the authors argue, that even though the majority of the energy will still be produced by conventional energy sources such as oil, coal and natural gas in the next couple of decades, the effect of renewables slowly integrated in the system will eventually become visible. (Scholten, 2018) Green energy slightly but steadily erodes the well-established oligopolistic markets, where producer-players such as Russia and The Organization

of the Petroleum Exporting (OPEC) countries have significant market power. According to the International Energy Agency`s (IEA) publication World Energy Outlook 2016, renewables are growing with the highest average speed of 2.6% annually, when nuclear is 2.3%, and fossil fuels are less than 2% per annum. At the same time, the investments are shifting to the site of green energy. (Appendix 1) (International Energy Agency (IEA), 2016)

Figure 1 presents the new prognosis of the IEA, released in 2019, for the renewable energy capacities in 2030 and 2040 in the strategically important regions around the globe. The rapid growth of renewable capacities of Asia, predominantly China, shows the leading position in both scenarios (Stated Policies and Sustainable Development), followed by the European Union and Northern America (mainly the USA). Reduction of renewable energy costs and innovations in digital technology offer tremendous opportunities for energy transition. According to the Stated Policies scenario (less environmentally ambitious), wind and solar power will provide more than half of the additional new-built capacity, and almost the total capacity in the ambitious Sustainable Development scenario.

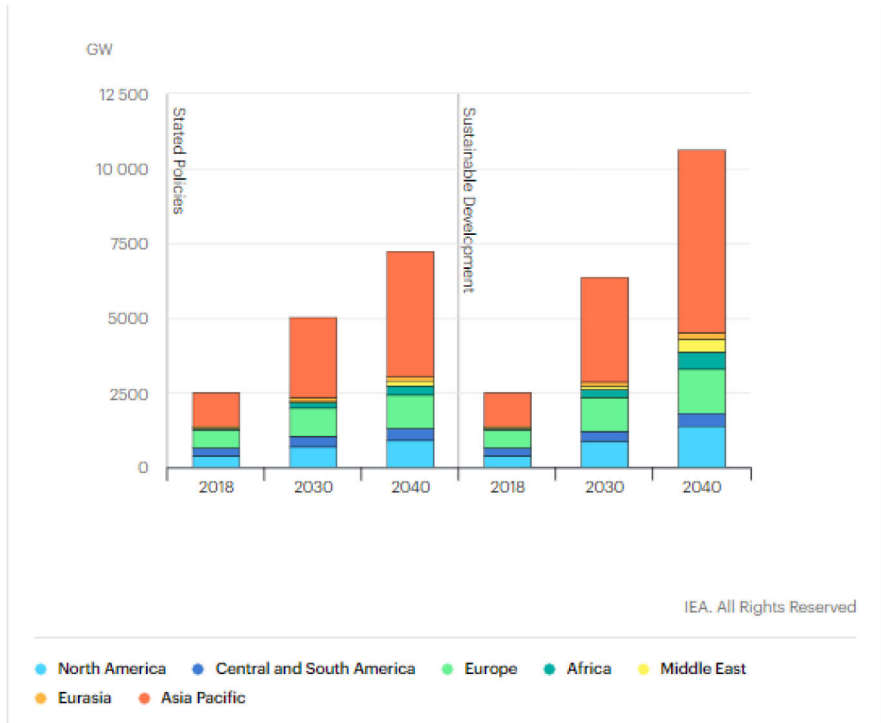


Figure 1. Renewable electricity capacity by region and scenario, 2018-2040 (IEA, 2019)

The Asian region (China, Japan and Korea) and the European Union are those countries, which Stated Policies and Sustainable Development scenarios for 2040 have similar targets in terms of

shares in the renewable energy – from 70-80% of the total added capacity, Figure 2. The rest of the countries shows less interest in increasing their carbon free capacities. The majority of the capacity installed is solar power (PVs), followed by wind and hydro. Wind capacities are most prevalent only in the European Union.

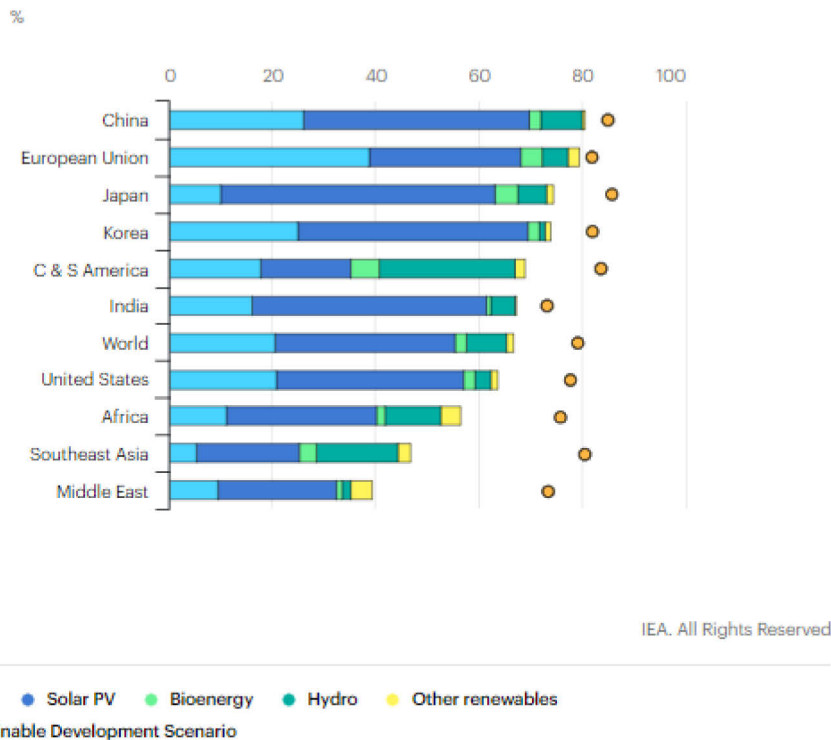


Figure 2. Share of different renewable energy sources by region in the Stated Policies and Sustainable Development Scenarios.(International Energy Agency (IEA), 2019b)

Although the renewable capacities are slowly gaining momentum, the conventional installed and planned capacities are not going to disappear anytime soon from the energy horizon. Fossil fuels will be still a larger share in the global energy mix during this century. (International Energy Agency (IEA), 2016) Moreover, there is no evidence whether renewable energy could satisfy the global energy demand at all, due to technological, economical and simply weather constraints. However, that does not mean not to take seriously the energy transitions. For example, energy giants such as the USA, China and Germany have already shown interest in competition for industrial leadership in green technologies and in investigation for access to rare raw materials, which could cause a potential bottleneck in progress. Examples include notable developments and plans to create super grids such as Desertec in the Sahara, the North Sea Offshore Wind

Network, or the North American interconnection. Overall, the biggest powers such as the United States, the EU, China, Russia, Japan, India, and OPEC countries are clearly working on the strategies to obtain maximum benefit and mitigate the shortcomings of the transition to renewable energy. (Scholten, 2018)

Another geopolitical dimension for assessing the control over the new growing market for renewable technologies is the number of research activities taking place in various regions (number of patents), the capital investments in green projects and the abundance of successful leading companies in new industry. For example, for the period 2001-2005, the patents in different renewable energy technologies were allocated the following way as it is shown in Table 1. (Scholten, 2018)

Table 1. Number of patents in renewable energy awarded within the period 2001-2005.(Scholten, 2018)

Wind Energy	Solar energy	Fuel cells
<p>Germany owned 24% of all patents in the world,</p> <ul style="list-style-type: none"> • Japan 23% • the US 10% • China 5% • Russia 5% • South Korea 5% • Denmark 4.5% • the United Kingdom 3%, • Spain 3%, and France 2%; 	<p>Japan owned 50% of all patents,</p> <ul style="list-style-type: none"> • South Korea 11.5% • the US 11%, • China 7% • Germany 6.5%, • Russia 1.5% • The Netherlands 1.5%, • Australia 1%, • the United Kingdom 1% • France 0.8%; 	<p>Japan owned 60% of all patents,</p> <ul style="list-style-type: none"> • The USA 14%, • Germany 7%, • South Korea 7%, • China 3%, • Canada 3% • the United Kingdom 2% • France 1%

From information gathered in Table 1, it is visible that the same countries are involved in research activities and investments. Therefore, it could serve as a signal for others to be aware of the new markets development. In the renewable energy game “the winners” are coming out Japan, The USA, The EU (especially Germany), China and Korea. So-called “losers” are those countries, whose economies are mostly dependent on the export of the fossil fuels, such as Russia and Saudi

Arabia. They will be in a critical situation, because of the reduction of the total net revenues from oil, coal and natural gas. (Scholten, 2018)

Geo-economics of the EU and consequences of German “Energiewende” for all Member States.

The European Union represents a unique system of different Member States (MS), cooperating with each other in one direction. Traditional geopolitical international relations do not apply in the EU model. Individual nations still act as independent actors but due to the supranational model of EU legislation, EU law has supremacy over member states law, with some exemptions. As such it's more apt to use the term geo-economic instead of geo-political when describing the EU energy policy. Even though the intergovernmental and bilateral relationships within the Union refers to complex and advanced form of governance, the energy system is considered rather weak and vulnerable. Due to disagreement on energy policy on a MS level, it lacks a consolidated energy approach. The EU government has centralised decision-making power system. The three main principles for the EU energy framework are: energy security, competitiveness and sustainability.

Authors of the book “The Geopolitics of Renewables” introduced the term geo-economics to describe the European Union energy policies. They explain that the absence of the coherent politics create an impression that European affairs are often marked by a power policy with soft means. The geo-economics usually puts politics and economics to be the part of the one game, or better to say the two sides of one coin, where the economic part is driving the political part and vice versa. Generally speaking, geo-economics highlights the economic balance between power and grammar of commerce between the MS and suggests that the structural characteristics of markets determines the effectiveness and ability of states to influence the system in their favor. However, from the angle of geo-economics, concepts such as welfare, status and prestige determine the political and economic behavior between EU MS, and not primarily energy security and autonomy. (Scholten, 2018)

The European Union is considered rather a successful political project of integrating the large capacities of variable renewable energy sources into a well-established energy system.

Nevertheless, fractions on the field of the internal conflict between the MS are becoming deeper and more obvious, as not in every case the individual energy policy of a MS goes in line with the European government`s suggestions.

One of the main examples in the changing structure of the European Energy System refers to Germany. Germany`s decision towards the green energy policies and energy transition (Energiewende in German) is considered as the major event of the geopolitical games within the EU in the last decade. As a main industrial and economical center in the EU, the German government started significantly reshaping its energy policy system since 2011 by implementing a new sustainable economy and rapidly increasing the share of renewable energy in the energy mix step by step. The German energy sector and Energiewende will be described in more details later in this chapter. The energy transition is changing the capacity allocation geography within the country. Most of the energy generation from renewables (mainly wind parks) is concentrated in the north of the country, whereas the largest consumers – industries are located in the south. The main issue is the lack of the sufficient infrastructure to connect northern and southern parts of Germany to provide secure electricity transmission. Furthermore, Energiewende is not operating without integration with the neighboring energy systems. It is a dynamic element and the direct and indirect economic and industrial reverberations are expected among the surrounding countries. Energiewende influences international relations of Germany in different ways in the north and south of the country. It is obvious that Germany`s transition to low-carbon solutions can lead to both increased cooperation and increased conflicts in Europe.

Since the Germany energy system is designed to support an increasing number of renewable energy sources, temporary congestion in power systems spreads to the country's neighbors. Therefore, they constantly increase the need for infrastructure adjustment on the borders and beyond. Changes in the distribution of generating capacities in Germany, the growing instability of electric networks and the falling in wholesale prices on the spot electricity markets have been shown to pose other important problems in this context.

German-Russian bilateral relationships

The geopolitics of Russia and the European Union, or more precisely in the case of this master thesis - Russia and Germany is mainly based on the exchange of Russian fossil fuel resources such as crude and refined oil, natural gas and metals (notably iron/steel, aluminum, nickel); for German part – primarily exports of the machinery, vehicles and vehicles components. Germany is Russia's the biggest trade partner after China and the Netherlands. (OEC, 2020) And for Germany is essential to continue the dialog with Russia, despite the sanctions put by Brussels on Russia, after annexation of Crimea in 2014 and actions in eastern Ukraine.

On Figure 3 is shown the resulting drop of trade relationship between Russia and the EU. Especially dramatically fell the import of Russian energy raw materials between 2012 and 2016. However, in 2016 the Russian imports started its recovery and in 2017 they increased by 21 %. In 2018 EU exports to Russia remained stable, whereas EU imports from Russia increased by 16%. The data is based on the Eurostat's COMEXT database. (Eurostat, 2018)

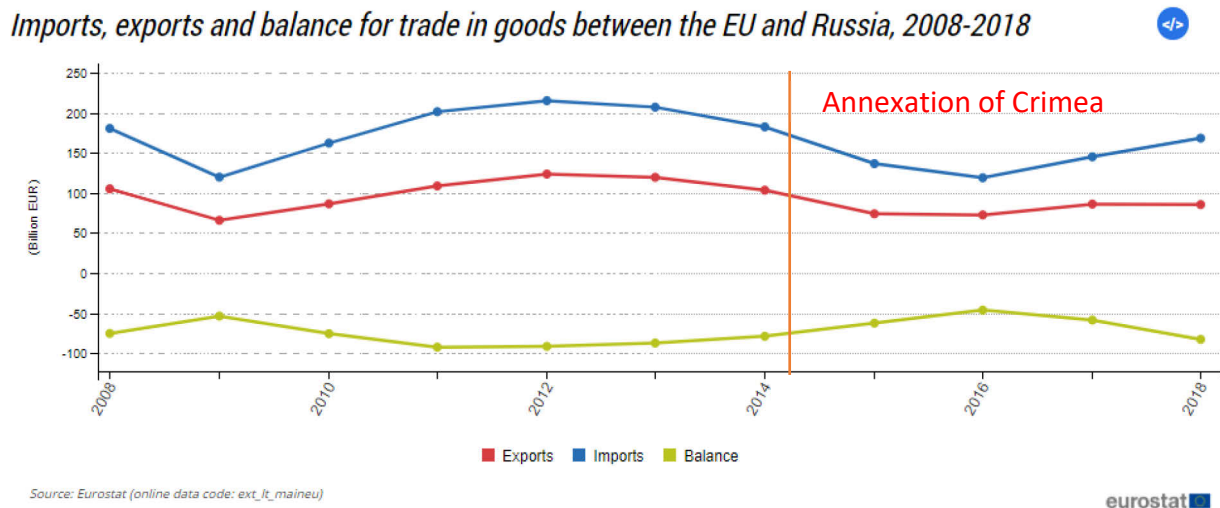


Figure 3. Imports, exports and balance for trade in goods between the EU and Russia, 2008-2018. (Eurostat, 2018)

In 2018 according to the data from Eurostat, Russian-German exchange in goods was the highest among all 28 EU Member states. Figure 4 shows the size of trade (imports on the right and exports on the left).

EU-28 imports of goods from Russia by Member State, 2018

	EUR million	% of Russia in extra-EU-28 imports
Germany	32 857	9.0
Netherlands	24 308	8.2
Poland	16 299	23.6
Italy	13 830	8.0
Belgium	9 916	7.3
France	9 543	5.4
Finland	9 263	46.4
United Kingdom	8 017	3.0
Hungary	4 873	18.8
Sweden	4 666	10.7
Lithuania	4 581	46.5
Greece	4 142	15.5
Slovakia	3 952	24.7
Romania	3 134	14.9
Bulgaria	3 130	35.5
Spain	2 952	2.2
Czechia	2 920	7.9
Austria	2 680	7.3
Denmark	1 707	6.5
Estonia	1 445	38.1
Latvia	1 304	31.6
Portugal	1 295	7.1
Ireland	551	1.7
Slovenia	400	3.4
Croatia	385	7.2
Cyprus	115	3.0
Luxembourg	12	0.5
Malta	5	0.3

Source: Eurostat (online data code: DS-018995)

EU-28 exports of goods to Russia by Member State, 2018

	EUR million	% of Russia in extra-EU-28 exports
Germany	25 985	4.8
Italy	7 596	3.8
Poland	6 760	15.6
Netherlands	6 066	3.9
France	5 357	2.7
Lithuania	3 974	33.9
Belgium	3 672	3.4
Czechia	3 498	12.9
Finland	3 336	12.7
United Kingdom	2 798	1.3
Austria	2 124	4.7
Spain	2 028	2.1
Sweden	1 948	3.4
Latvia	1 831	41.5
Slovakia	1 547	13.5
Hungary	1 532	7.9
Romania	1 068	6.9
Estonia	875	18.9
Denmark	828	2.3
Slovenia	802	9.0
Ireland	520	0.7
Bulgaria	381	4.3
Greece	231	1.5
Portugal	202	1.5
Croatia	148	3.1
Luxembourg	134	6.1
Cyprus	21	0.7
Malta	1	0.1

Source: Eurostat (online data code: DS-018995)



Figure 4. EU-28 imports/exports from/to Russia by Member State in 2018. (Eurostat, 2018)

The increase of the supply of natural gas is related to recent main project between Germany and Russia, the pipeline Nord Stream I and II, which goes directly from Russia to Germany under the waters of the Baltic Sea. The first pipeline started operation in 2013 with an annual capacity of 55 billion cubic meters of natural gas. The twin pipe Nord stream II is another 55 billion cubic meters (bcm) of natural gas per annum, which will result in 110 bcm, after completion of the project approximately in 2020. Some sceptics say that Germany is going to replace the phase-out capacities of nuclear and coal energy with Russian gas, therefore the project Nord stream II undergoes pressure and new sanctions from the USA and others.

Switching to natural gas, will have some environmental benefits, as combustion of natural gas results in significantly lesser amount of the CO₂ emissions. For Germany, it could be a solution for improving the situation of the total greenhouse gas (GHG) emissions and meeting the targets of the Paris Agreement (PA) in 2030. Nevertheless, to meet the targets of the PA in 2050 Germany

should undertake more effective measures and probably reduce the energy dependence on fossil fuels radically. For Russia it could be a signal to foresee the changing pattern of German and European Energy System in order not to lose its leading position.

One of the alternatives for replacement of the natural gas after 2030 could be renewable gases, major of which are hydrogen, biomethane and synthetic natural gas. In this paper hydrogen (source technology Power-to-Gas) will be discussed as cross-sectoral energy vector, altering the system towards total decarbonisation. Therefore, the investigation is made for Russia as a potential producer of the carbon-free hydrogen (based on renewables or nuclear), and for Germany as the main consumer.

1.2 The European Union and the Paris Agreement

The global climate challenge driven by the enormous impact of human activities pushes the governments of all countries globally to adapt or constrain tighter environmental legislation. The International Panel on Climate Change (IPCC), existing from 1988, is responsible for informing the policy makers at all levels about the state of the environment and the measures that could be implemented for climate change mitigation and adaptation and the time constraint. (IPCC, 2013)

In the last 30 years there have been globally concerted steps to tackle climate challenges and conferences of the United Nations Framework Convention on Climate Change (UNFCCC). One of the results of such engagements is the Paris Agreement within the UNFCCC 2016, which holds 195 signatures of different countries. The agreement is looking towards decarbonisation in different sectors of human activities defined by IPCC in the 2°C scenario report. The target is to reduce greenhouse gases (GHGs) 80-95% by 2050. However, the IPCC panel did not specify the internal emission reductions, its pathway and the amount of emissions handled by introducing the worldwide carbon market. Therefore, the strategies, that the individual governments adopt, is country specific and reflects the country's economic condition, its national resources and geopolitical conditions. (European Commission, 2011)

The European Union was one of the first to sign and ratify the PA. According to the annual GHG inventory report written by European Environment Agency (EEA), the five most polluted anthropological sectors in European Union (Figure 5) are: energy and transport sector (emissions from fossil fuel combustion), industrial processes and product use, agriculture, land use, land use change and forestry (LULUCF), and waste management. (Eurostat, 2016)

Greenhouse gas emissions, analysis by source sector, EU-28, 1990 and 2017
(Percentage of total)

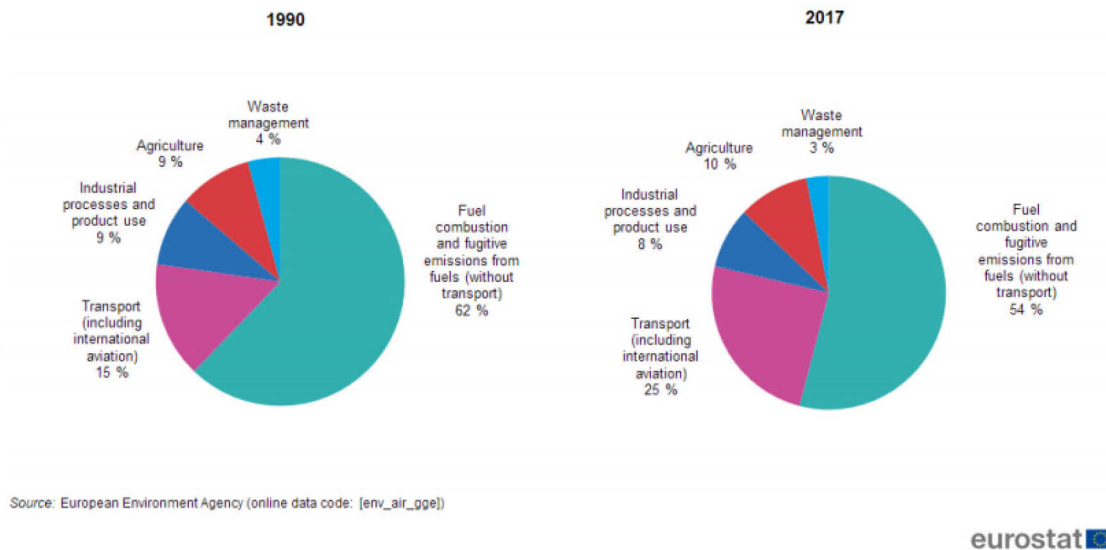


Figure 5. Greenhouse gas emissions, by source sector, EU-28, 1990 and 2017 (% of total). (Eurostat, 2016)

The decarbonisation of energy and transport sectors (80% GHG emissions in 2017) is the priority target. Therefore, the European Union is currently tightening legislation towards climate change problems. In Table 2 the targets for reduction of GHGs in the European Union are presented. The Paris Agreement defines renewable energy and energy efficiency as main contributors to the achievement of the following targets: in 2030 – reduction of climate changing gases by 40% and by 80-95% by 2050 compared to the level of 1990.

Table 2. EU climate reduction targets according to Paris Agreement. (Climate Action Tracker, 2020)

	year	2020	2030	2050
Reduction in GHG emissions (compared to 1990 level)		20%	40%	80-95%
Share of renewable energy in total energy consumption		20%	27%	
Energy savings		20%	27%	

1.3 The European Energy Policy: objectives and challenges

For 20 years the worldwide energy law underwent a strong transformation due to energy transition, or in other words restructuration of the energy system by liberation of energy markets and introduction of the decarbonised power source (renewable energy). The energy law serves

as basis of the political agenda, as it is bonded with the environmental and economic indicators of the country. (Heffron et al., 2018)

The energy legislation in the EU was established for many years. However, the well-structured and mandatory energy policy of the EU, with which we are familiar today, was set by European Council only in 2005. The EU was one of the first who mentioned about its radical changes and in 2007 started structuring its energy policy. In 2015 the Energy Union Strategy was formed, which became the backbone of the new European energy policy. The EU stands for affordable, secure and sustainable energy supply for each MS. At the same time this strategy shows the joint work on the issues of climate change and energy dependence of the EU. The Energy Union Strategy constitutes five mutually-consolidating dimensions: energy security, a fully-integrated internal energy market, energy efficiency, climate action and research and innovation. (European Commission, 2016)

The policy is aiming to comprise the main energy challenges by 2030 in line with the PA 2°C objectives. Among those are:

- minimum 40% reduction in total GHG from 1990 levels
- increase to 27% of the share of renewable energies in energy consumption
- increase of 20% (minimum) – 30% in energy efficiency
- The interconnection of at least 15% of the EU's electricity systems

(European Commission, 2016)

According to the European Commission, the data of EU's total GHG emissions in 2018 decreased by 2.1% (the data without calculation of LULUCF and international aviation). The reduction of GHG was slowed down mainly due to the increase of the transport emissions by 0.5%. However overall sectors showed a decrease, the most successful was the power sector – dropping by 5.3%. The overall picture from 1990 up to 2018 is showing a similar tendency, the drop in emissions is 25.1%, more precisely Power and electricity sector (33.3%), Industry (27.6%), Waste (43.4%), and agriculture (19.8%), however the emissions in the transport sector raised by almost a quarter. (Climate Action Tracker, 2020)

One of the main instruments for reduction of GHG in the EU is the EU Emission Trading System (ETS), which is managing and minimizing emissions from the power and industry sectors and EU domestic flights, whereas transport, building, light industry and agriculture are covered in The Climate Action Regulation (CAR) and left to discretion of the MS, see Figure 6. The CO₂ emissions of the EU ETS sectors are controlled by the specific amount of the emission allowances that are announced annually. Moreover, from January 2019 Market Stability Reserve (MRS) takes place, which is a mechanism for monitoring oversupply of emission allowances and for improving system resilience to severe shocks by regulating auction permits. (Climate Action Tracker, 2020; European Commission, 2020b)

Considering the growing amount of CO₂ from the non-ETS sector, especially transport, some EU governments, for example Germany, are planning to introduce carbon dioxide allowances in 2020. Thus, encouraging citizens and manufacturers to switch to more environmentally friendly vehicles.

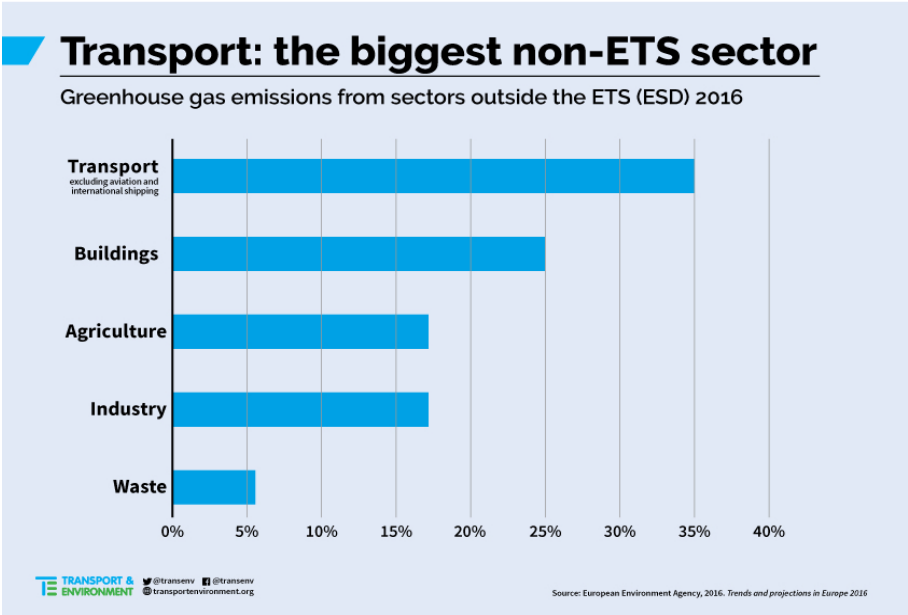


Figure 6. Non-ETS sector, percentage of emissions by sector. (Transport & Environment, 2019)

The Renewable Energy Directive (EU) 2018/2001 (RED II) from December 2018 determines the EU’s 2030 target – increasing renewable energy in the power mix to a minimum 32% of the EU’s gross final energy consumption. Another cornerstone legislation instrument for meeting decarbonisation targets is The Energy Efficiency Directive 2012/27/EU (EED) and its amending

directive (2018/2002), setting targets of at least 32.5% of energy efficiency by 2030. In the energy values, the EU total energy consumption should not exceed 1273 million tonnes oil equivalent (Mtoe) of primary energy and/or 956 Mtoe of final energy. (European Commission, 2020a)

At the end of 2018 the European Commission released the draft of the EU Long-term Strategy “A Clean Planet for all”. The work comprised eight different emission reduction scenarios, which are divided by achieving goals of the PA and meeting the scenarios of 2 °C and 1.5 °C, possible scenarios for meeting the 2050 carbon neutrality emissions target. In the statement of the EU Commissioner for Climate Action and Energy, Arias Cañete, the most ambitious scenarios are actually the only one that are complying with the PA and are priority for the EU. (Climate Action Tracker, 2020)

As one of the first initiators of the COP21 to sign and ratify the PA in 2015 and to tightly bind different branches of its economy, the European Union has established the emission reduction targets. In Table 3 the decarbonisation targets are compared for the European Union and Germany. The total carbon dioxide (CO₂) reduction is stated as 80-95% based on the level of the year 1990. Massive integration of renewables (mainly wind turbines and PVs) and improvement of energy efficiency are considered as the main contributors to achieve the set targets.

Table 3. Comparison of the decarbonisation targets of European Union and Germany. Adapted from (Climate Action Tracker, 2020)

	EU	Germany
2030		
RES in final energy consumption	27%	30%
RES-Electricity	45%	65%
RES-Heating		
RES-Transport		
CO2 emissions Reduction (to 1990)	40%	55-56%
Energy Efficiency	27%	
2050		
RES in final energy consumption		60%
RES-Electricity		80<%
CO2 emissions Reduction (to 1990)	80-95%	80-95%
Energy Efficiency		50%

German Energy Policy.

All the members of the European Union are reshaping their energy policies in the most beneficial way for their own case, mainly establishing their strategy on the country specific geographical location, current energy mix and the availability of natural resources. In the case of Germany, the government decided to introduce the most ambitious pathway. Therefore, the German example is important to analyze, as for developing countries it could be a template for reconstructing their fossil fuel-based economy.

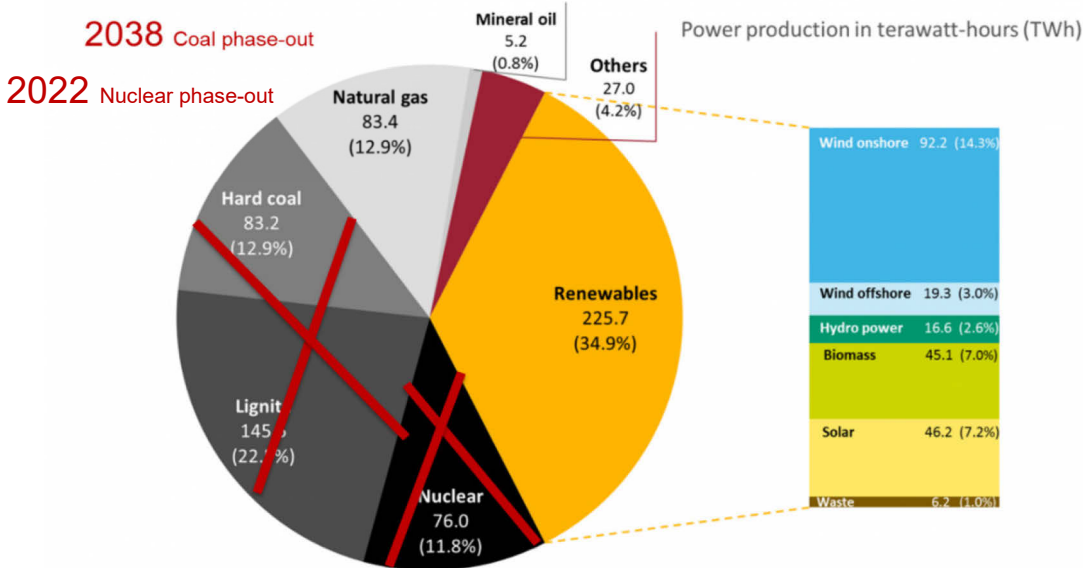
Analyzing the climate ambitions and incentives of all 27 countries in Europe, Germany is undoubtable attracting attention. Besides the fact that the country has a leading position in the economic sector in Europe, and among the world, it is also the first in terms of the availability of innovations in the energy sector. The first country with a rich industrial history that poses a great challenge to the world, abandoning hard coal and building up a new decarbonized energy system.

In 2016, Federal Ministry for the Environment Nature Conservation and Nuclear Safety of Germany introduced new goal to reach “nearly greenhouse gas neutrality by mid-century”. In November 2019 the draft of the first environmental law in Germany was adopted by the national

parliament, the German Bundestag. In the law stated, that Germany commits to achieve the GHG neutrality by 2050 as a long-term strategy. The strategy was accepted despite the failure of the German government to accomplish GHG reduction target for 2020. (European Commission, 2016)

Current German legislation adapts to the European Energy Union framework and has developed its own strategies and directions for research. The Bundestag decides on the country’s federal laws. The Renewable Energy Act I and II (EEG I and II) and the Energy Industry Act (EnWG) are among the most important energy laws.

One of the first announcements from the Bundestag regarding the changes to the power mix is the nuclear phase-out scheduled in 2022. After the nuclear accident in Fukushima, the German government could not close their eyes on the anti-nuclear protests, started in the mid-1970 and decided to eliminate atomic energy. In January of 2020, a final strategic report with shutdown schedule for each power plant by the Coal Commission was released, where the year 2038 was stated as the latest deadline for coal and lignite energy phase-out. (Litz, 2019)



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Figure 7. Share of energy sources in gross German power production in 2018, the phase out of the capacities of nuclear, lignite and hard coal. Adopted from Clean Energy Wire, 2019 (Clean Energy Wire, 2020a)

From the power mix (Figure 7) arises the question, how Germany would be able to replace almost half of the installed capacity (47.2 %, nuclear + lignite + hard coal). In the short-term prospect, the energy can be balanced by introducing more variable renewable energy (wind turbines and PVs) and flexible natural gas power plants. Therefore, it is expected that the consumption of natural gas in Germany and as well as in Europe will grow by 2030. However, even though gas turbines are considered a “cleaner” option as the progress releases 50% less of carbon dioxide (CO₂) compared to the combustion of coal, methane (CH₄) emissions are still present (especially during extraction of natural gas from the gas fields – methane leakage). Methane is 30 times more potent as a heat-trapping gas than carbon dioxide, and thus contributing to higher intensity to the Earth’s temperature rise and infeasibility of the target of 80-95% CO₂ emission reduction.

In Figure 8 is shown the amount of GHGs emissions in million tonnes CO₂ equivalent and the reduction targets, compared to the level of 1990.

Sector	1990*	2018*	2030*
		[reduct., comp. to 1990]	[reduct., comp. to 1990]
Energy	466	311 [33%]	175-183 [61-62%]
Buildings	210	117 [44%]	70-72 [66-67%]
Transport	163	162 [0.6%]	95-98 [40-42%]
Industry	284	196 [31%]	140-143 [49-51%]
Agriculture	90	70 [22%]	58-61 [31-34%]
Other	38	10 [74%]	5 [87%]
Total	1251	866 [31%]	543-562 [55-56%]

*In million tonnes CO₂ equivalents.

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Figure 8. German Greenhouse gas emission reduction targets 2030 by sector. Adopted from the Clean Energy Wire 2019 (Clean Energy Wire, 2020a)

To achieve the total decarbonisation, and not to lose the leading economic position, the German government is developing a new energy strategy. On the Global Ministerial Conference on System Integration of Renewables in October 2019 in Berlin, Peter Altmaier, German Federal Minister for Economic Affairs and Energy, noted in his speech, that the climate challenge can be solved by introducing the new market – hydrogen market, where Germany should be the world’s leader, beating Japan, China and “Germany’s energy transition rests on three pillars as follows:

1. Expansion of solar and wind energy

2. Digitalisation in the energy sector
3. Sector coupling

1.4 Green Hydrogen in German legislation

In Germany, the regulations that concern Power-to-Hydrogen (PtH or PtG) are not stated in the energy law. Rather, due to the cross-sector technology, several different legislative documents have to be taken into account, but also their regulatory responsibility is distributed among different ministries. The following legal laws / ordinances for power-to-hydrogen are essentially relevant:

- Federal Emission Control Act
- Federal Emission Control Ordinance
- Energy Industry Act
- Renewable energy law

Power-to-gas (PtG) – production of electricity-based gases. Synthetic gases can be generated using various processes and technologies. The basis of the power-to-gas process is an electrolysis with water and electricity input. In Germany, the use of renewable electricity (direct purchase or on the balance sheet) for power-to-gas plays a special role, on the one hand as a decarbonisation option for gas applications and on the other as long-term energy storage for integrating renewable energies. (Dena, 2019)

In Germany, the PtG process is currently being tested in around 25 research and pilot projects. Another approx. 30 projects are planned. At most locations, hydrogen is generated by electrolysis and then used or fed into the gas network; at some locations, the hydrogen is further processed into methane using CO₂. The installed capacity is almost 25 megawatts electric (MWel). The currently produced amount of electricity-based gases is not relevant for the energy supply. Due to the low production capacities and the pilot or demonstration character of most projects, which are often only operated temporarily or at certain hours. (Dena, 2019)

The legal framework which could identify and fully cover definition of PtG is absent in Germany or in the European Union in general. The legal classification of PtG as a facility should be established in the context of existing legal definitions (energy) of storage, end-users and production in accordance with relevant national laws. The role of the legal documents can be compared as gatekeepers that are constraining the output of the application from the level of certain legal measures to specific technologies. For example, at the state of the final consumption the total costs derived a higher due to extra network charges (transmission + distribution network), consumer taxes, and other charges. The question arises if the application is the business of transmission or distribution operator. Another issue relating to PtG legislation is that different stages of the process of production, transportation, supply and end use, are covered by outdated preexisting energy laws, which were not uniquely created to cover PtG. Features such as electrical energy storage are not defined in individual laws but exist as part of preexisting laws. Power-to-gas is difficult to fit under one certain class of technologies, as it can be used cross-sectors and transforms from molecules to electrical energy to heat and vice versa. Therefore, it requires comprehensive update of the German and European legislation to avoid the overlapping of the controversial statements in the law.

The current law on electricity and gas supply (Energy Industry Act – EnWG) states that hydrogen (H₂) produced from water (H₂O) electrolysis with at least use of 80% energy from the renewable energy can be classified as biogas with privileged connection (Figure 9).

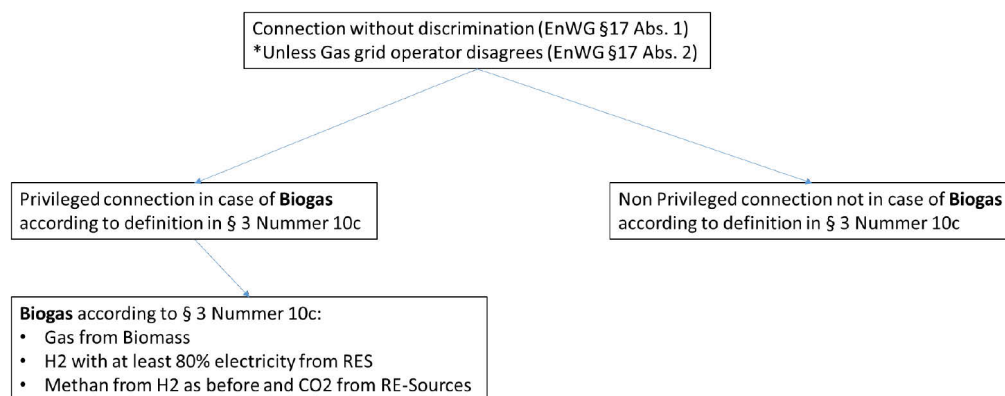


Figure 9. Scheme on the privileged and non-privileged connection in case of biogas. Adopted from (BMWi, 2017)

Implementation of the Renewable Energy Directive (RED II) in the context of renewable gas

Dialog process paper by Deutsche Energie-Agentur GmbH (dena) states the adjustments according RED II (EU, 2018) to the German national law that must be implemented by June 30, 2021. The following laws and regulations are potential for the processing:

- Federal Pollution Control Act (BImSchG): Adjust GHG quota targets
- 37th Ordinance on Federal Pollution Control Act (37. BImSchV): Electricity supply for PtG systems, detection regulations for green electricity
- 38th Ordinance on Federal Pollution Control Act (38. BImSchV): sub-quotas for advanced fuels and biofuels from waste and residues, multiple credits for e-mobility and rail transport, H2 credits for sub-quota, biofuels from cultivated biomass
- 10. Ordinance on Federal Pollution Control Act (10. BImSchV): Fuel quality for hydrogen, adjustment of the blending rates
- Energy Tax Act: Offsetting biofuels on shipping (taxation of fuels in shipping)
- Biomass electricity sustainability regulation: Sustainability of the input materials
- Gas network access regulation

A key focus in the implementation of RED II at the national level will be the introduction of proof of the gases origin. The associated questions are the classification and standardization, the design of a trading system, the compatibility with the existing trading systems for electricity and biogas and with the other countries' systems and in particular sustainability factor with specific quality requirements for the different types of gas. (Dena, 2019)

Key points of Chapter 1.

- 1) Rapid growth of renewable energy globally is attempting to bring radical changes on established geopolitics of the fossil fuels. Green energy slightly but steadily erodes the well-established oligopolistic markets, where producer-players such as Russia and OPEC countries have significant market power. Among all of the regions around the world Asia (mainly represented by China), the European Union and Northern America are taking the first three places in the renewable energy race in terms of the installed capacity (in GW) in 2030 and 2040 according to IEA. The majority of the capacity installed is solar power (PVs), followed by wind and hydro. Wind capacities are most prevalent only in the European Union.
- 2) One of the main examples in the changing structure of the European Energy System refers to Germany's decision to move towards the green energy policies and to support the renewable energy transition (Energiewende). Compared to the Paris Agreement CO₂ emission reduction targets, provided by the EU, Germany shows stricter decarbonisation measures in many indexes, such as share of the renewable energy in the final energy mix and per sector, CO₂ emission reduction (Germany is aiming to a 100% CO₂ cut by 2050) and energy efficiency.
- 3) Energiewende influences on the neighboring countries in Europe. The phase-out of nuclear and coal capacities in 2022 and 2038 will change the trading export/import of the net transfer capacities between countries. In the mid-term up to 2030, it is expected that intermittent renewable energy sources together with flexible natural gas power plants will replace nuclear and coal capacities. Nevertheless, in order to reach total decarbonisation in 2050, the role of fossil fuels (natural gas) have to be replaced by renewable gases, such as biomethane, synthetic methane and hydrogen.
- 4) In recent years German government is relying more on the green and carbon-free hydrogen, which acts as decarbonisation and sector coupling (molecules, electricity and heat) tool for reaching CO₂ emissions neutrality in 2050. Green hydrogen can provide support for intermittent renewable energy sources as long-term energy storage medium and help to reduce GHG emissions of the sectors, which are impossible to electrify (industry, heavy, marine and air transportation).
- 5) Regarding the energy policy, green hydrogen technologies – Power-to-Gas – are not stated in the energy law. Rather, due to the cross-sector technology, several different legislative documents have to be taken into account, but also their regulatory responsibility is distributed among different ministries. The role of the legal documents is one of the main barriers that prevent the scaling up PtG on a commercial level. At the state of the final consumption the total costs derived a higher due to extra network charges (transmission + distribution network), consumer taxes, and other charges. Therefore, it requires comprehensive update of the German and European legislation to avoid the overlapping of the controversial statements in the law.

Chapter 2. Hydrogen’s potential role in the European Energy decarbonisation strategy. German experience.

2.1 Introduction to Hydrogen as an energy carrier.

Hydrogen is expected to become one of the main future energy carriers. This element is interesting from the energy perspective. Hydrogen (H_2) is the most abundant and simple molecule in the world. Hydrogen is a colorless, odorless gas and consists of only one proton and electron and, unlike fossil fuels, does not have any carbon structure, therefore is considered as environmental friendly without any impact on the air quality when “burnt”. Hydrogen exists mostly in the form of different compounds, most commonly within water molecules (H_2O) and cannot be found independently in a pure form.

Hydrogen is referred to the smallest element among all members of the Mendeleev’s periodic table. As the lightest gas (about 8 times lighter than methane or natural gas), however its gravimetric higher heating value (HHV) is 3 times higher than methane, meaning per kg the amount of energy release at 25 °C is 142 MJ/kg. In the clean “burning” reaction with oxygen, hydrogen forms water and releases heat. For the fuel gas, gravimetric or mass HHV is not applied widely in practice. Table 4 shows the difference between natural gas’s and hydrogen’s physical properties. Usually, different fuel transportation and storage tanks or pipes are limited to particular volume, therefore, it is decided to refer to volumetric HHV and not to gravimetric HHV in comparative assessments of the gaseous and liquid fuels. (Bossel & Eliasson, 2002b)

Table 4 Comparison of the physical properties of hydrogen and natural gas (methane). (Bossel and Eliasson, 2002)

	Dimensions	Hydrogen	Methane
Density at NTP	kg/m ³	0.09	0.72
Gravimetric HHV	MJ/kg	142.0	55.6
Volumetric HHV	MJ/m ³	12.7	40.0

Figure 10 represents the comparative overview of some energy carriers at different pressures and forms and their volumetric HHV. At different pressures hydrogen has the lowest values of the volumetric HHV compared to different forms of natural gas.

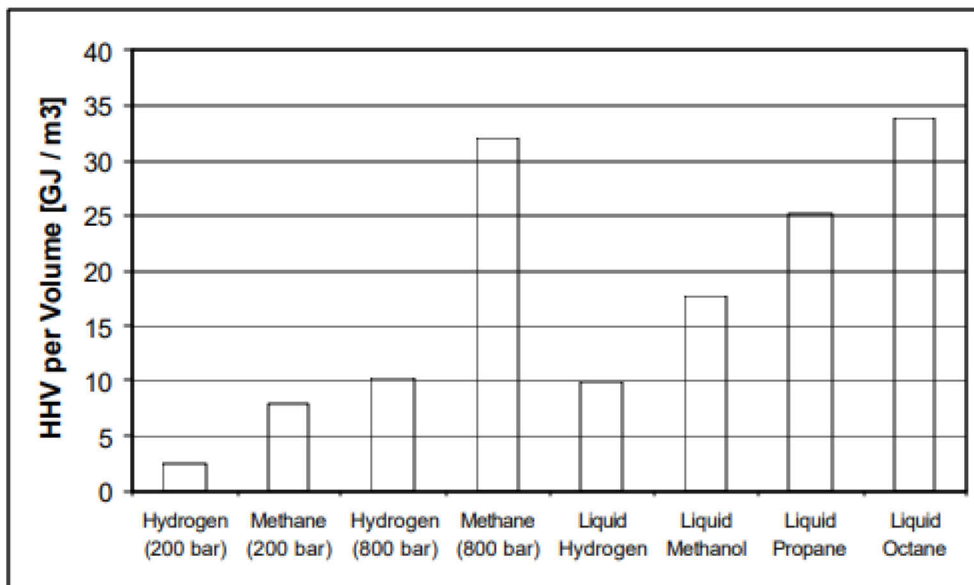


Figure 10. Volumetric HHV energy density of different fuels (Bossel and Eliasson, 2002)

2.2 Colours of hydrogen

Hydrogen can be produced in different ways. According to Kaufeci *et al.*, the environmental effect of hydrogen is usually visualised by different colours. On Table 5 colours grey, blue, turquoise, green and yellow are presented. All of them are dependent on the feedstock and origin of energy for hydrogen production and how carbon-neutral is the resulting product (hydrogen). *The grey colour* refers to the production of hydrogen from natural gas through the steam methane reforming (SMR) technology. The SMR is traditional and the most common way corresponding to 95% of all hydrogen produced in the world. The cost for production of 1 kg of H₂ is 1.5 € and is considered relatively low to the other methods. (International Energy Agency (IEA), 2019a) Important to mention, that in this master thesis SMR is one technology which is available on a large scale. The steam methane reforming process involves two steps: reformation of natural gas and shift reaction. In the second step known as a water gas shift, the end products are hydrogen and carbon dioxide in the ratio 1:9. Therefore, for 1 kg of H₂ there is 9 kg of CO₂ released to the atmosphere. (Colorado School of Mines)

The blue colour represents the same technology as for grey – SMR system, however, in order to minimize or avoid CO₂ emissions, Carbon Capture and Utilisation/Storage (CCUS) is added. According to Kaufeci *et al.* CO₂ emissions are still present, however in negligible amounts. The cost of blue hydrogen is considered higher due to CCUS, and can increase more depending on the geographical conditions and the distance for the CO₂ transportation and storage. (Kayfeci et al., 2019)

The turquoise colour represents converting natural gas by means of pyrolysis into hydrogen. (TNO, 2019) The technique is novel and has been developed in the last 5 years. The idea is that natural gas is heated up to a high temperature in oxygen absent conditions and then thermally decomposed to hydrogen and solid carbon or graphitic carbon, which further can be used in steelmaking or in the manufacture of electric cars' batteries. The technology is considered as a competitive alternative to steam methane reforming, but is not yet demonstrated at scale.

The yellow and green colours of hydrogen refer to technology electrolysis, which principle is to split the water molecule into hydrogen and oxygen by means of electricity. In the yellow case the electricity is supplied by nuclear energy or even integrated together with nuclear reactors in some cases. Such a method is considered carbon neutral, however, due to the nuclear waste, is not a preferable option among the environmental activists. For production of green hydrogen electricity from renewable generators (PVs, wind turbines) is usually used. The costs for green hydrogen remain high compared to other methods. However, a steep reduction of costs for electrolyser (up to 70%) is expected after 2030. This technology is gaining a big momentum around the world and is considered as a number one instrument for reaching targets of the Paris Agreement.

Table 5. Overview of different colours of hydrogen according to the energy source and footprint of CO₂ emissions. Adapted from (Kayfeci et al., 2019)

Colour	Energy Source and type	CO ₂ emissions	Cost-efficiency (CAPEX costs are not included)	Availability
Grey	Natural gas, SMR	9 kg CO ₂ /kg H ₂	1.5 €/kg H ₂	Large scale

Blue	Natural gas, SMR + CCUS	0.82-1.12 CO ₂ /kg H ₂	2.0 €/kg H ₂	Pilot plant scale
Turquoise	Natural gas, Pyrolysis	CO ₂ neutral	1.8-3.00 €/kg H ₂	Under development
Yellow	Nuclear energy, Electrolysis	CO ₂ neutral, nuclear waste	3.5-7.00 €/kg H ₂	Pilot plant scale
Green	Renewable energy, Electrolysis	CO ₂ neutral	4.7-9.2 €/kg H ₂	Pilot plant scale

Hydrogen has already shown the potential as an energy carrier. The growing interest of energy and industrial leading companies around the world could be a signal that clean hydrogen will play a main role in decarbonising fuel dependent sectors. The barriers for massive integration of green hydrogen are still the high costs and small-scale availability of the innovative technologies, which would probably not reach desirable levels till 2030. Nevertheless, the future of renewable hydrogen is more optimistic, than it appears from a quick glance. The traditional, grey hydrogen is intensively used in the industrial sector, however, as was mentioned before, it is rich with CO₂ emissions (9 kg of CO₂ to 1 kg of H₂). Overall it represents 3% of the GHG emissions globally and is one of the targeted areas for energy transition. Looking at the options for the industry decarbonisation, two of them appear, blue hydrogen (same as grey, but with CCUS) and green (electrolysis). (International Energy Agency (IEA), 2019a)

The cost factors that play the decisive role are: the prices of natural gas, CO₂ cost per ton, CCUS cost and cost of the renewable electricity. The grey hydrogen price in the European market today is starting at 1.5 €/kg H₂, which gas price is at around \$3/MMBtu and is unstable and rather volatile and might increase in the next decade. (IEA-2019) Another factor affecting the traditional production way of hydrogen is the change in the environmental law, setting strict carbon budget and implementing the carbon pricing system for all sectors (power, industry, heating and transport). The current cost for the emitted ton of CO₂ in the EU stands in the range of 20 – 25 €/ton CO₂. However, the increase in the CO₂ certificates is expected to rise to 30-40 €/ton CO₂ in 2030, which will result in an additional 0.5 €/kg H₂ to the cost of the conventional hydrogen (without taking into account the high volatility of the gas market). (International Energy Agency

(IEA, 2019a) Blue hydrogen is a cleaner option than grey and easier to implement than green, as it serves as a retrofit to existing SMR facility and requires an additional element of CCUS. The barrier is the cost of the carbon capture and storage unit, where carbon dioxide compression, transportation and utilization/storage have most effect on the expenses and relate to 50-70 €/ton CO₂, according to the IEA in 2019. The technology requires to be scaled up, however, political opposition against it significantly prevents any further developments. An example could be the Hunterston project in the UK and RWE Goldenbergwerk in Germany.(MIT, 2016a) Nevertheless, the German government in the beginning of 2020 opened up again the discussion on including CCUS technology back to national energy strategy as an instrument to tackle climate change. (Clean Energy Wire, 2020b) The project H2morrow could serve an argument on the statement above. (Equinor, 2019) Since CCUS exists on a pilot scale in Europe, but the level of technological readiness is sufficient to implement on an industrial scale, investments and standardisation is necessary to bring the costs down and scale up the method. (MIT, 2016b) Similar problems concern turquoise hydrogen with pyrolysis.

The electrolysis method has different factors, which hinder scaling up easily. The main factor is the cost and efficiency of the electrolysis itself, the cost of the electricity generation and water availability. The yellow hydrogen is usually associated with the nuclear generation. The pilot projects around the world, mainly in the USA (STAR-H2 project, Modular helium reactor for hydrogen production (H2-MHR)), China, Europe (projects RAPHAEL, EUROPAIRS) and Russia (MHR-100SE). (International Atomic Energy Agency, 2013) The generated heat from the nuclear reaction can be utilized for the electrolysis purposes (for example High temperature (steam) electrolysis (HTSE)) and at the low peak times the cheap nuclear energy can be supplied to the electrolysis. The costs are lower than for the electrolyzers by renewables, however, the obstacles of the nuclear based hydrogen is the different political restrictions on the nuclear capacities, capital and fuel costs, as well as fuel availability and nuclear waste management.

According to the study of Glenk and Reichelstein, the break-even price of green hydrogen in Germany is estimated at the level of 3 €/kg. (Glenk & Reichelstein, 2019) The price was calculated for the small and medium businesses and does not refer to the large industrial facilities. To have a clear understanding of the hydrogen price level, the following conversions were made. A

kilogram of hydrogen has approximately 33.3 kWh, therefore 1 kWh of H₂ costs 9 euro cents pro kWh. For comparison, Table 6 represents an overview of fossil fuel costs in euro cents pro kWh. However, by 2030 the cost of kg H₂ is expected to be reduced to 2.5 €/kg. (Glenk & Reichelstein, 2019)

Table 6. Overview of the different fossil fuel costs per kWh. Adopted from (NEP, 2019) (with a conversion rate 1 euro = 0.89 pound)

Fuel	Gas	Oil	LPG	Butane	Propane	Coal	Hydrogen
Cost (cent/kWh)	5.62	7.64	7.87	26.29	13.15	6.85	9

At the moment the cost of green hydrogen is estimated around 4.7-9.2 €/kg H₂ (Table 5), which is the highest among all the colours. (International Energy Agency (IEA), 2019a) The energy experts prognose that the increase of the installed capacity of the electrolyzers to industrial scales will help to reduce the total costs by 70% in next 10 years. Another important factor is the cost and availability of renewable energy. In the recent decade, the learning curves of the wind and solar energy technologies were reduced significantly, therefore providing an optimistic forecast, that green hydrogen will follow a similar path. In the European Union the capacity of renewable energy to be installed is limited and soon will reach the threshold. The regulations for construction of the wind parks become stricter due to public protest, which caused some projects in Germany to be cancelled. The solar irradiation is less strong than in the countries located on the equator, the poor availability of land for harvesting energy in Europe does not give any chances for further deployment of renewable energy. The solution for green hydrogen can be found in establishing international relationships with the potential export countries of hydrogen. Currently, Northern Africa, Brazil, Middle East and Russia could be considered as the main applicants. The potential exporters of green hydrogen will be discussed in more detail at the end of this chapter. (International Energy Agency (IEA), 2019a)

The hydrogen economy is on the edge of starting its rapid expansion and the main question arising, is not which hydrogen production method will be the most prominent, but whether all of the available hydrogen innovation technologies would be enough to start replacing fossil fuels. Therefore, it is important to establish the market and infrastructure readiness conditions for

hydrogen now. The first step would be a start with methane based hydrogen (blue and turquoise) 2020-2030, and the next step would be a gradual introduction of green hydrogen in the energy mix from 2030-2050. No doubts, that the electricity based hydrogen will provide the pathway to the total decarbonisation of the main energy based sectors and represents the future flexible and sustainable energy system. The current cheaper options for hydrogen could become less preferable due to future changes of the cost structure, as dependency of the global economies on the fossil fuels is tending to weaken within a timeline of 2050 and beyond.

Another competitor to the CO₂ free hydrogen is the electrification of the energy systems in some sectors (transport and heating). Different options for decarbonisation could be looked and discussed from different angles, and not as a competition, but more in a combination; “team” work. However the alternative of electrification as a means of decarbonising the mentioned sectors is beyond the scope of this work, and will not be further analysed here.

2.3 Power-to-gas, Power-to-X, system overview

Power-to-Gas (PtG) system represents a technology that merges two important energy carriers such as gas and electricity. The coupling of gas and electricity sectors becomes possible thanks to the water electrolysis. This can be called a breakthrough moment as sector-coupling changes the whole design of the energy system by implementing greater flexibility. Traditionally, electricity demand was the main driver for electricity production and the electricity market equilibrium was met at every particular point of time in the power grid. Therefore, the electricity prices varied during peak and low demand periods, as more expensive technologies enter the electricity market driven by higher demand (merit order concept). The energy system is conventionally based on the three pillars: energy production, energy transmission/distribution and energy consumption. However, with the increasing share of renewable energy sources, the fourth pillar – energy storage is gaining more importance. There are different reasons for this. The picture of the present European energy system is presented as the oversupply of the installed capacity (fossil fuel). (Faure-Schuyer, 2016) With utilization of different means of energy storage, especially hydrogen storage, the energy losses are minimized, the total costs are reduced, as well as the prices for electricity. However, the described above situation will take place only under

specific market conditions, when the costs of the storage technologies will be compatible with the costs of the installed generation technologies.

When electricity and gas networks are interconnected, the excess for long time (over month) storage of the green electricity (from renewable energy) appears. The existing gas infrastructure forms an efficient and effective storage option, especially for energy systems in which energy is provided decentrally. Storage in the gas network means that fluctuating energy generation from wind and solar can be decoupled from energy consumption. At the same time, the power grids are stabilized. The PtG system provides storage options for longer time periods and seasons. The gas infrastructure is becoming a green back-up for the energy transition. In this “two-energy world”, green gases in the form of hydrogen and synthesis gas, help to make the energy sectors transport, heat supply and electricity generation quickly climate-neutral. (DVGW, 2019)

Power-to-gas concept

The concept of Power-to-Gas system (PtG) is established on the four technological steps (presented on Figure 11): the surplus electricity generated from the renewable sources (wind turbines, PV installations), the electrolyser that produces hydrogen and oxygen by dissimilation of water molecules, the methanation option may be added for production of synthetic natural gas (SNG), compression system and storage or injection into the gas grid (either pure hydrogen or mixed with natural gas) systems.

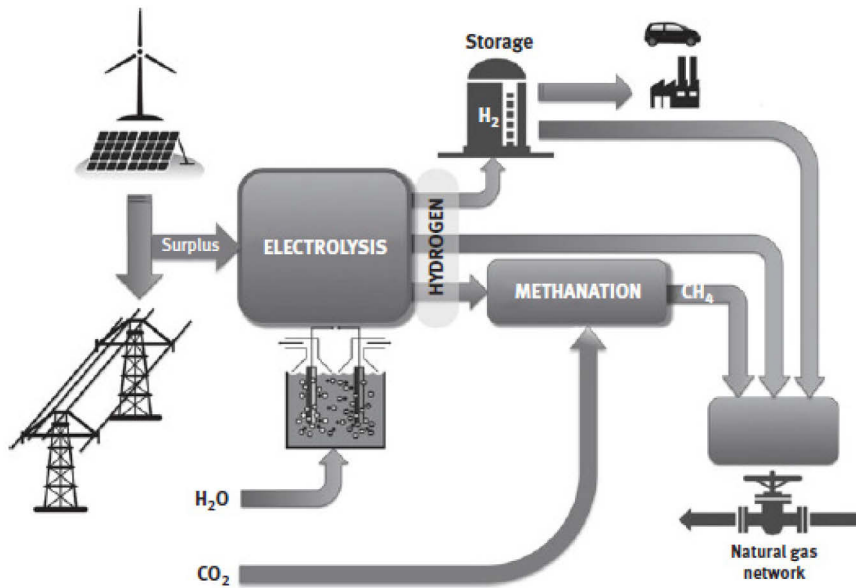


Figure 11. Power-to-gas concept. Source (Boudellal, 2018)

Electrolysis

The electricity for the electrolysis part is supplied from the variable renewable energy sources. The principle of electrolysis lies in the production of hydrogen and oxygen by separating water molecules under electrical current conditions. The process is well-known globally and exists already for more than a century, however only 4% of the world hydrogen production relates to electrolysis. Due to the marginal costs of such method, electrolysis loses its competitiveness in the market, yielding to the conventional SMR. Nevertheless, with significantly increasing popularity of the renewable energy sources and their cheap, or nearly “free” generated electricity, a new horizon opens as well for the green hydrogen production and development of a relatively large energy market. (Bucy et al., 2016)

The electrolyser consists mainly of electrodes, electrolyte material with a membrane or diaphragm and DC power connected. In addition, auxiliaries such as a current rectifier, a water demineralization unit, a water pump and a cooling system and hydrogen purification system are designed to support the electrolyser. On Figure 12 the scheme of the electrolyser is represented as an electronic cell, where anode and cathode are the electrodes that attract positive and negative charged ions respectively. Therefore, on the cathode accumulates hydrogen gas, and on the anode oxygen gas. The electrolyte material, depends of the type electrolyser and ensures, that charged particles will reach the right electrode. The most common electrolyte for alkaline electrolyzers is sodium hydroxide (NaOH) or potassium hydroxide (KOH) dissolved in water. (Bucy et al., 2016)

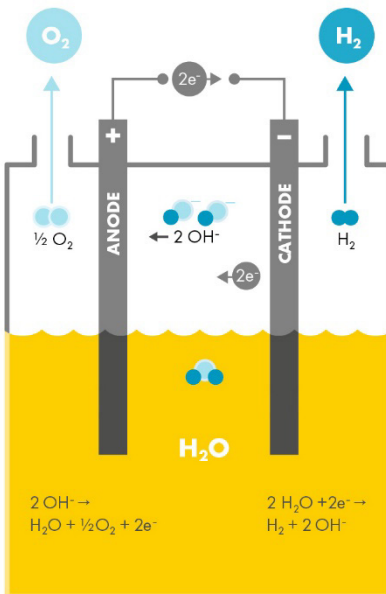


Figure 12. Scheme of alkaline electrolysis. Source Hydrogen Europe

Technological state of art represents three available types of electrolyzers: alkaline (with liquid electrolyte), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), summarized in Table 7. The presented electrolyzer are referred to as low-temperature electrolyzers. High temperature electrolyzers are operating with feedstock steam instead of water at the range of 900-1000 C (Appendix 2). Solid Oxide Electrolyser Cells (SOEC) can serve as an example. They provide higher voltage efficiency rates 81-86%, as the electrical input for steam reaction is lower than water reaction in electrolysis. (Appendix 2) The alkaline electrolyzer is considered as the only option commercially available on the industrial scale. Therefore, costs and size of the application

are more optimistic, compared to all other technologies presented. However, for the last decade the Research and Development (R&D) of PEM electrolyser is gaining momentum and shows better results than its alkaline competitor. PEM has significant potential in capital expenditure (CAPEX) costs reduction, whereas in the case of alkaline, all possible cost optimisation methods have been applied. According to Bertuccioli *et al.*, 2014, in 2030 CAPEX costs of PEM will drop to 400 €/kW.

Table 7. Comparison and overview of commercially available electrolyser technologies (low temperature). Adopted from (Bertuccioli et al., 2014)

		Alkaline	PEM	AEM
Development status		Commercial	Commercial medium and small scale applications (≤ 300 kW)	Commercial in limited applications
System size range	Nm ³ _{H₂} /h kW	0.25 – 760 1.8 - 5300	0.01 – 240 0.2 - 1150	0.1 – 1 0.7 -4.5
Hydrogen purity		99.5% – 99.9%	99.9% – 99.9%	99.4%
Indicative system cost	€/kW	1000-1200	1900-2300	N/A
Voltage efficiency	%	62-82	67-82	67-82

Methanation

In case of the SNG, the methanation option is added to the electrolysis part, where the synthesis of methane by hydrogenation of carbon monoxide or carbon dioxide happens. Existing options for methane production are catalytic (thermochemical process under high temperatures (between 200 and 700 °C) and in presence of usually nickel catalyst) and biological (the hydrogen and carbon dioxide molecules are synthesized by the help of microorganisms under anaerobic conditions in the temperature range 20-70 °C). The source of CO₂ for SNG should be environmentally neutral, for instance, from biomass or Direct Air Capture (DAC). (European Commission, 2018a)

Besides being a long term energy storage and balance for fluctuating renewable energy supply, hydrogen can be utilized in different applications. In a pure form it is prepared for the fuel cells and hydrogen combustion turbines. Afterwards, it is used for transportation purposes, from passenger cars to aircrafts. Green hydrogen can be used as a feedstock in different industrial

processes and replaces conventional grey hydrogen. Mixed with natural gas or in a pure form, it can be supplied for the heating systems in residential buildings and industries. The discussion on the sectoral applications of hydrogen continues in more details at the end of the 2nd Chapter, as it is essential to first to analyze the size of the potential hydrogen market in Europe and Germany.

2.4 Potential demand of hydrogen in Europe, Germany

Studies for the European Union on the energy markets overview in 2030, 2050

“A clean planet for all”, study by the European Commission

The descriptive paper “A Clean Planet for all” was prepared by The European Commission in 2018 on the topic of the decarbonisation of the main energy sectors and possible ways to achieve the targets of the PA and 2 °C and 1.5 °C scenarios. The paper distinguishes between two types of the scenarios: Baseline scenario and eight Decarbonisation scenarios. The aim of the baseline is to represent the resulting trajectory that current and planned EU climate policies would have on GHG emissions. It assumes all current policies planned until 2030 are achieved. It does not incorporate policies post 2030 or the impact of changing of policies for individual member states. Every Decarbonisation scenario represents hitting at least the minimum 2 °C target, or above 80% GHG reduction. In a case of 1,5 °C target, total reduction of CO₂ emissions is achieved. In all scenarios the assumptions on the political aspects, import/export, the role of Energy Efficiency and Renewable Energy Directives are fixed and do not vary. The important assumptions that reflect the possible picture of the European energy market in 2030 and 2050 are the Primary Energy Consumption (PEC) and net fuel imports. PEC falls in 2030 by 26% and in 2050 by 35% compared to 2005 levels. Energy production in Europe overall decreases by 28% compared to 2005. The energy based on fossil fuel, faces reduction by 88% in the PEC mix, whereas renewable energy capacity more than doubles in 2030 compared to 2005 (Figure 13). The net fuel import is also affected according to predictions in the Baseline Scenario, decreasing by 33% in 2050 compared to 2005 level, from 980 Mtoe to 670 Mtoe. Mainly the decrease is provoked by the rapid reduction of fossil fuel capacities in 2030. (European Commission, 2018b)

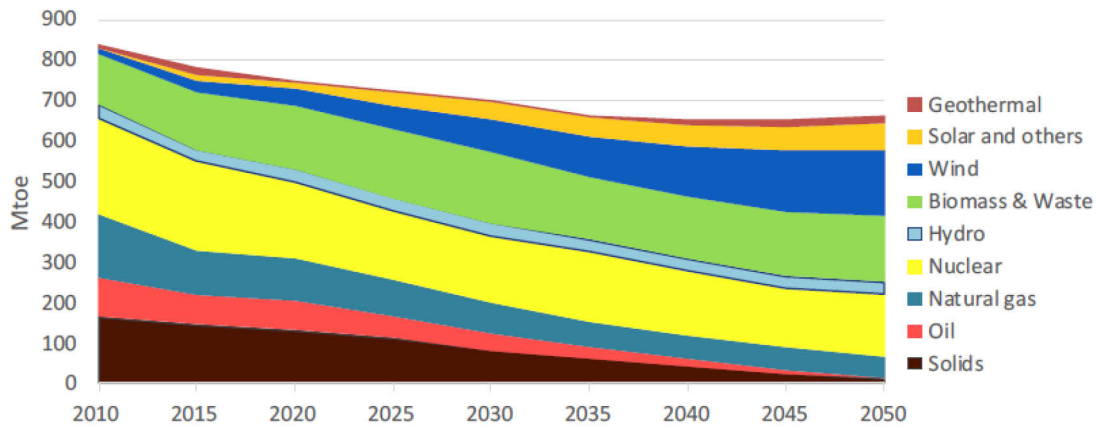


Figure 13. Primary energy production in the Baseline Scenario. Study “A Clean Planet for All”. (European Commission, 2018b)

Despite the reductions in the primary energy consumptions, the demand for electricity increases drastically. Electricity becomes the dominant energy carrier, contributing to the decarbonisation by electrifying the transport sector (electrical vehicles), residential sector (heat pumps) and industrial sector. On Figure 14 the demand for electrification is shown. By 2050 73% of electricity will be generated from renewable energy. The nuclear and gas power capacities will be present in 2050, whereas solid fossil fuels and oil almost disappeared from the capacity mix.

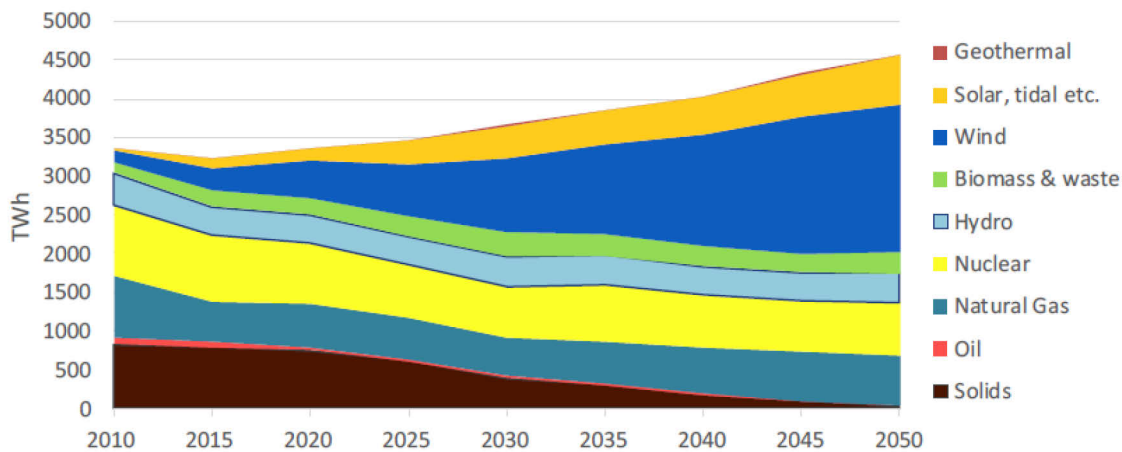


Figure 14. Electricity generation in the Baseline Scenario. Study “A Clean Planet for All”. (European Commission, 2018b)

For this master thesis only the scenarios associated with decarbonisation of the all sectors via integration of hydrogen technologies, instead of the fossil fuel based, are analysed. On Table 8, two scenarios are chosen from the eight presented in the EU paper: H2 and P2X (e-fuels). They refer to the first group of the scenarios in the study “A Clean Planet for All”. They aim to achieve

80% of GHG reduction and are driven by the integration of zero-carbon energy carriers, such as electricity, hydrogen, and e-fuels (synthetic fuels that are produced from green hydrogen and carbon dioxide using electricity). On Table 8 the H2 scenario represents a broad integration of hydrogen as a main energy carrier, which covers all main energy based sectors (power storage, transportation, industry and heating) and is an alternative to replace natural gas. In a system, where variable renewable energy sources take the main part, hydrogen as a chemical energy storage can become the best long-term solution, as it could be produced during the low energy demand, stored and used for covering the peak demands or utilized as a fuel for fuel cells and as a raw feedstock for the large industries. The scenario refers to the hydrogen infrastructure as well, highlighting that the 10-20% penetration of hydrogen into the natural gas grid is possible, without massive upgrades of the system, however, for further development, the natural gas system should be prepared for higher rates of hydrogen (>50%). (European Commission, 2018b)

In the scenario P2X (Table 8), the e-fuels are presented as the main energy vector. E-fuels are synthetic gases or liquids that were synthesized from the reaction of green hydrogen and carbon dioxide, obtained from environmentally friendly sources, such as biomass or DAC. E-fuels can substitute gas and oil, as they have the same chemical structure. Synthetic ammonia is also considered as hydrogen based carbon-free fuel. This e-fuel brings special attention, as ammonia could be used not only in the chemical industry, but also as a relatively cost-efficient medium for storing and transporting hydrogen. In Chapter 3 storage and transportation options of hydrogen are discussed in more details. The conventional infrastructure does not require new investments, as is perfectly suitable for e-fuels. (European Commission, 2018b)

Table 8. Scenarios Hydrogen and Power-to-X, adopted from the EC publication “A Clean Planet for All” (European Commission, 2018b)

Scenarios	Main Drivers	GHG target in 2050	Major common assumption	Power sector	Industry	Buildings	Transport sector	Other drivers
Hydrogen (H2)	H2 in industry, transport and building	- 80% GHG	*	Power sector is nearly decarbonized by 2050. Strong penetration of RES facilitated by system optimization	Use of H2 in targeted applications	Deployment of H2 for heating	H2 for HDVs and for LDVs	H2 in gas distribution grid
Power-to-X (P2X)	E-fuels in industry, transport and buildings				Use of e-fuels in targeted applications	Deployment of e-fuels for heating	E-fuels for all types	e-fuels in gas distribution grid

*

Main Market assumptions

- Higher energy efficiency post 2030
- Deployment of sustainable, advanced biofuels
- Moderate circular economy measures
- Digitilisation
- Market coordination for infrastructure deployment
- BECCS present only post-2050 in 2°C scenarios
- Significant learning by doing for low carbon technologies
- Significant improvements in the efficiency of the transport system

Figure 15 represents the main energy carriers in final energy production. In the hydrogen based scenarios the prevailing role belongs to electricity, more than 41% among other carriers. In H2 scenario, the share of hydrogen is a bit less than 20% of the total. In the case of the e-fuels, the share in final energy production stands at 10%. In millions of tonnes of oil equivalent (Mtoe) it corresponds to 142 Mtoe and 90 Mtoe respectively. (European Commission, 2018b)

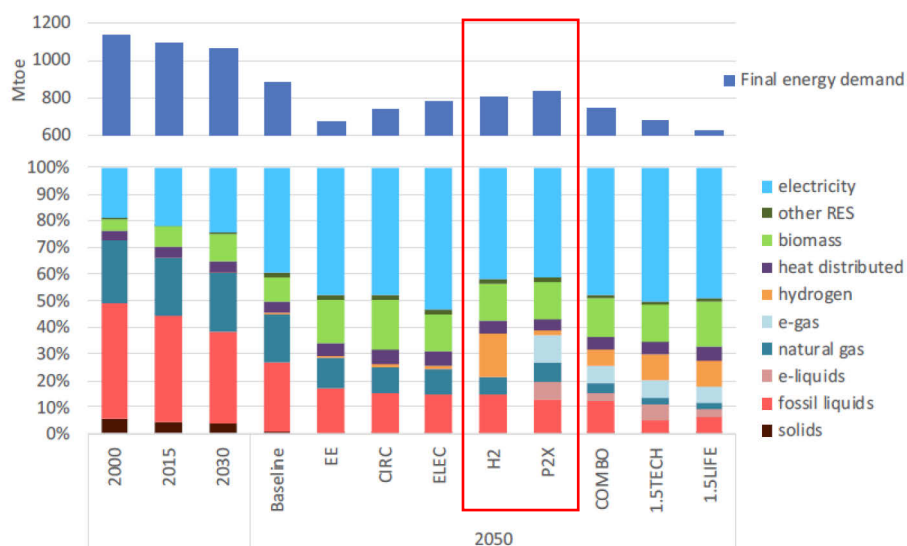


Figure 15. Share of energy carriers in final energy production. (European Commission, 2018b)

In the case of the sectoral usage of hydrogen and e-fuels, Figure 16 shows the allocation of the carbon free fuels according to four sectors (transport, industry, power and residential). On Figure 16 (A), hydrogen-based scenario H2 has the highest consumption of hydrogen. Transport and industry sectors have approximately the same hydrogen consumption, one third of the total, followed by residential and power sector. Nevertheless, important to note, in all other scenarios hydrogen (mentioned in the study “A Clean Planet for All”) is present, and is indicated mainly in transport and power purposes. (European Commission, 2018b) The transportation sector is considered one of the most problematic in question of GHG emissions, therefore fuel cell technologies for light and heavy vehicles are essential tools to reach the decarbonisation target. The hydrogen for the power sector is also shown in all scenarios. For the energy systems based on the variable renewable energy generation, the long-term seasonal storage applications is a necessary tool to support the whole system. So far, PtG, is the only method to store large amounts of electrical energy for a long time. Figure 16 B represents sectoral allocation of e-fuels. Residential sector has the highest share of e-fuels consumptions, approximately 40%. Synthetic natural gas can be utilized for heating purposes with the same

infrastructure that is designed for natural gas. The next sectors are industrial, followed by transport and power.

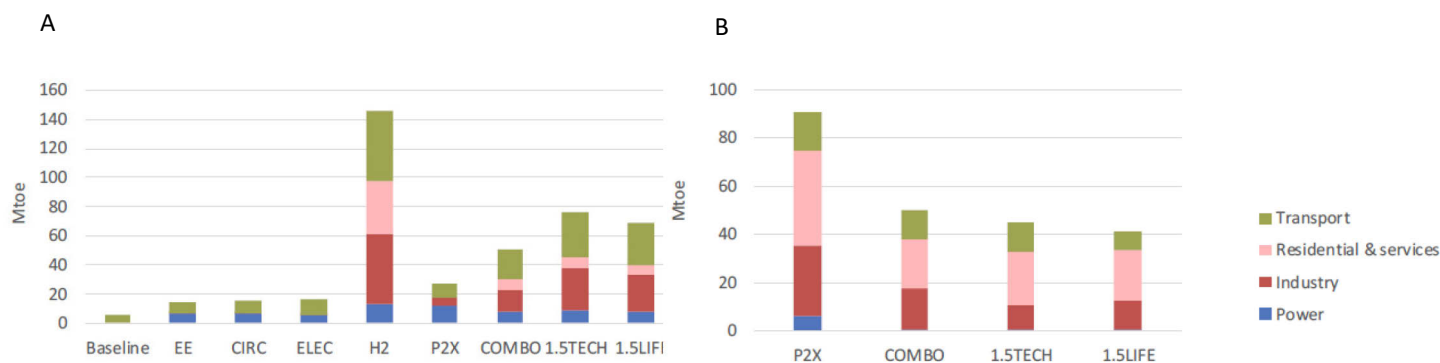


Figure 16. A. Consumption of hydrogen by sector. B. Consumption of e-fuels by sector (European Commission, 2018b)

The hydrogen based scenarios show that the hydrogen demand in 2050 can reach market levels and provide an attractive environment for development of the hydrogen economy. In the case of the e-fuels, hydrogen presents as an intermediate step, where the gas is generated by electrolysis and later upgraded to the required e-fuel. Looking at Figure 17, the size of the hydrogen market is nearly the same as the fossil fuel market, and serving as a signal for reshaping of the strategies of the global energy leaders.

Hydrogen Roadmap Europe, a study by Hydrogen Europe and Fuel Cells and Hydrogen Joint Undertaking

Hydrogen Europe is the European association on hydrogen and fuel cells. It combines many partners, more than 160 industry companies, 78 research organisations and 21 National Associations. The activities of Hydrogen Europe are focusing on the assistance for the companies related to hydrogen to become competitive on the market, by formulating effective public policies for the industrial players and providing coordination and academic support for the policy-makers as well.

In 2019 a roadmap 2050 for effective realisation of hydrogen economy in the EU was released by Hydrogen Europe. This report describes an ambitious scenario for hydrogen deployment in the EU to achieve the 2° target. The ambitious scenario is based on the perspective of the global Hydrogen Council, input from Hydrogen Europe (representing the European hydrogen and fuel cells industry). On Figure 17, the hydrogen demand for different sectors is presented. According to the authors, hydrogen could provide up to 24% of total energy demand, or up to ~2.250 TWh of final energy demand in the EU by 2050.

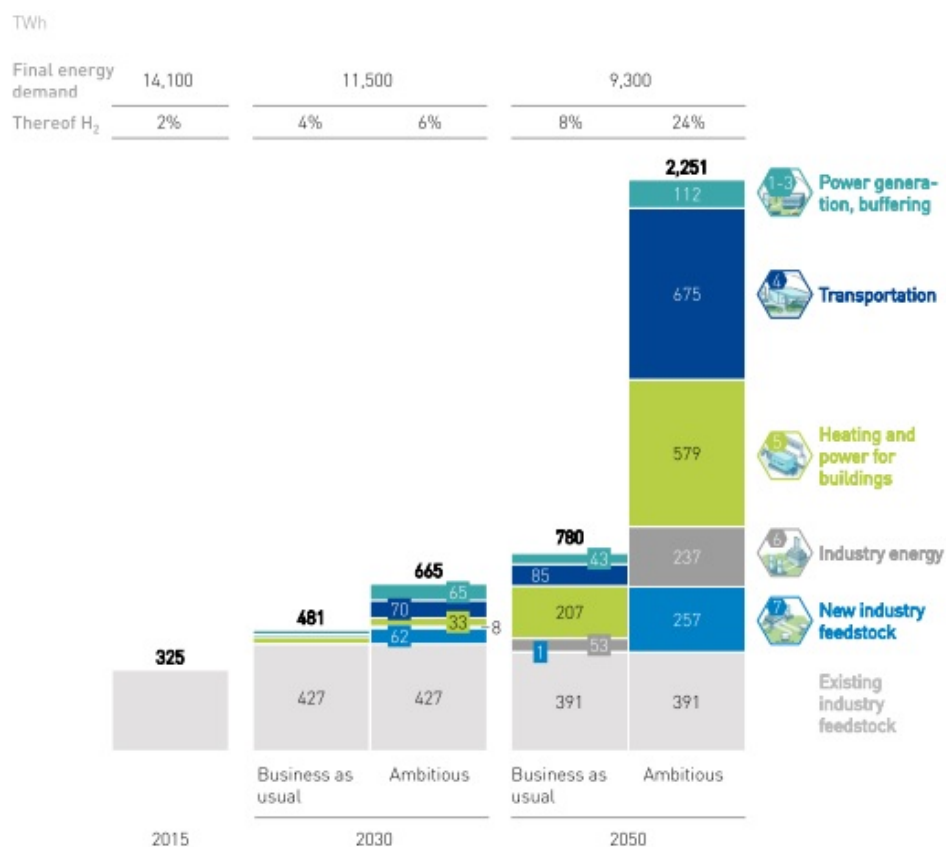


Figure 17. An ambitious scenario for hydrogen deployment in the EU to achieve the 2-degree target, description of hydrogen demand in Europe by sector. (Europe Hydrogen, 2019)

Compared to the scenarios from “A Clean Planet for All”, the Hydrogen Europe Roadmap shows significantly higher hydrogen demand. On Table 9 the main characteristics are gathered together to determine the difference between the hydrogen association (more ambitious) and the European Commission (more realistic) scenarios.

Table 9. Comparison of the hydrogen scenarios. (Red indicates the highest demand sector, blue indicates the lowest). Adopted from (Europe Hydrogen, 2019), (European Commission, 2018b)

Studies	“A Clean Planet for all”, the EC		Hydrogen Europe
	H2	P2X	
Total H2 demand (Mtoe)	142	90	193.6
Sectors (% of the total demand)			
Power generation	9	8	5
Transportation	32	17	30
Heating and power for building	25	44	26
Industry	34	31	39

Studies on the German hydrogen markets, overview in 2030, 2050

Overview of different literature on the potential green hydrogen demand in Germany in 2050.

(Based on the dena study) (Jensterle, Narita, Piria, Samadi, et al., 2019)

Germany has recently added green hydrogen to the Energiewende concept, previously powered mainly by the large expansion of the renewable sources and increase of the energy efficiency. The role of hydrogen is long-term and enables penetration in different sectors. Therefore, the first German National Hydrogen Strategy is now under way and will be released in the first half of 2020. Three main drivers for hydrogen are meeting the climate change targets, energy supply diversification and leadership in technological innovation. For Germany, green hydrogen is expected to be a tool for decarbonising mainly industrial and transport sectors, and to a smaller extent, power and residential (heating) sectors. (Jensterle, Narita, Piria, Samadi, et al., 2019)

The study of Jensterle et al. covers in total 18 scenarios from 6 studies on hydrogen development in Germany that aim to reach the target of 80-95% GHG reduction. All analysed research papers were published from and of 2015. The focus was put on the observation of the main drivers for the demand of hydrogen in 2030 and 2050. Authors mentioned, that energy system adaptations for hydrogen integration varied significantly depending on the level of the targeted GHG reduction 80% or 95%. The demand for hydrogen is fixed between 300 and 600 PJ annually, or representing up to 10% from primary energy demand. An important aspect to mention, is that Germany is considering not only hydrogen as a product, but also synthetic fuels based on hydrogen. These numbers are not added to the total demand of hydrogen, thus, we consider that overall demand of green hydrogen (also for the e-fuels) is significantly higher, as, according to the authors, the role of Power-to-X (synthetic fuels) is larger than hydrogen. Regarding the level of readiness for hydrogen infrastructure, the scenarios propose several options. First, hydrogen will be blended with natural gas in the currently operating gas infrastructure until the technical threshold of 20%. Secondly, the gas infrastructure will be upgraded for the higher tolerance of hydrogen. Third, the new hydrogen grid infrastructure will be designed and built. (Jensterle, Narita, Piria, Samadi, et al., 2019)

Table 10 contains different data on the demand of hydrogen and synthetic fuel in Germany in 2050. Six different scenarios were chosen by Jensterle *et al.* Demand for the synthetic fuels is higher than for pure hydrogen as the end-product. Despite the relatively low demand for pure hydrogen, the overall demand for PtX is high. By the overall demand for PtX is meant that power-

to- hydrogen is an intermediate step for synthetic fuel production, thus the demand for hydrogen is included there as well.

Table 10. Role of hydrogen and other synthetic fuels in the German scenarios in the final energy demand. Adopted from (Jensterle, Narita, Piria, Samadi, et al., 2019)

Scenario name	Hydrogen demand in PJ	Synthetic fuel demand in PJ	Total PtX demand in PJ
KS95	328	344	672
85_offen	121	430	551
85_H2	386	681	1067
85_PtG	0	1212	1212
TM80	463	595	1058
TM95	562	2707	3269

Table 11 comprises the hydrogen share of the demand in the main sectors – transport and industry. The scenarios that are non-zero are marked with red colour. In 2030 the shares of the demand for transportation and industry are not exceeding 11% due to the initial stage of the hydrogen economy. In 2050 the numbers are much higher up to 40% both for industrial and transport sectors.

Table 11. Hydrogen (H2) and synthetic fuel (SF) demand in transport and industrial sectors in selected scenarios. (Shown in % in transport and industrial sectors). Adopted from (Jensterle, Narita, Piria, Samadi, et al., 2019)

% of the sectoral demand	KS95		85_offen		85_H2		85_PtG		TM80		TM95	
	H2	SF	H2	SF	H2	SF	H2	SF	H2	SF	H2	SF
2030												
Transport	3	0	3	0	2	9	10	2	0	11	0	0
Industry	2	0	2	0	0	4	0	11	0	6	0	0
2050												
Transport	23	-	23	41	10	2	27	22	0	39	0	39
Industry	5	-	10	39	0	18	0	20	0	22	0	0

German Network Development Plan 2035 (Szenariorahmen zum Netzentwicklungsplan Strom 2035, Version 2021)

The new draft of the scenario framework for the electricity development plan for 2035, (version 2021) was released in January 2020 as a result of the cooperation between the German transmission system operators (TSOs) 50Hertz, Amprion, TenneT and TransnetBW. (Drees et al., 2020) The updated version of the draft assumes a clear flexibility in all researched scenarios. These include, for example, making the conventional generation plants more flexible with an increased decoupling of electricity and heat generation, the increased use of demand-side management and an intelligent and flexible use of new electricity applications, especially power-to-x technologies. All four German TSOs are welcoming the development of electricity demand and the underlying drivers of sector coupling (electro mobility, power-to-gas, and power-to-heat). The paper generates several scenarios with different importance for new power applications (especially power-to-gas systems). Depending on the configuration, the scenario variations depicted can focus on avoiding bottlenecks in the distribution or transmission network. (Drees et al., 2020)

According to the location of the power-to-gas installations, the majority of the plants produce hydrogen for local needs in industrial locations. It is assumed that there are no alternative hydrogen generation technologies on site. The plants are used accordingly, since there must always be enough hydrogen available for the downstream chemical industrial processes. Also due to the high investment costs of power-to-gas plants, the plants will be designed for high full load hours. A total of around 3,500 full-load hours per year are assumed for these systems according to the report of the TSOs. (Drees et al., 2020)

Authors also mentioned one example, regarding the competitiveness of the synthetic methane. According to the study, a market price for fossil natural gas of € 26 / MWh. In addition, the use of natural gas incurs costs of around € 10 /MWh due to the CO₂ emissions. Therefore, for the end user, the use of fossil natural gas is € 36 / MWh. The synthetic methane, on the other hand, can be used without additional CO₂ costs. The power-to-methane system can therefore always be operated economically if a low electricity price ensures that the methane can be produced for less than € 36 / MWh. Assuming an efficiency of 60%, this is only the case for electricity prices below € 21.6 / MWh. (Drees et al., 2020)

Table 12 represents the result of the study, conducted by the four German TSOs, and summarised the installed capacity of the Power-to-Gas installations in different scenarios in 2035 and 2040.

The majority of the PtG capacity installed is designed for the green hydrogen production and only 0,5 GW is for the synthetic methane. (Drees et al., 2020)

Table 12. Installed capacity for the Power-to-Gas applications. Adopted from NEP 2035. (Drees et al., 2020)

	Status 31.12.2018	Scenario NEP 2030 (2019)	Scenario NEP 2035 (2021)			
			A 2035	B 2035	C 2035	B 2040
PtG installed capacity (GW)	< 0,1	3	3	5	8	7,5
PtG power generation (PJ)	-	-	9,3	16,3	20,8	25

2.5 Overview of green hydrogen application by sector

Hydrogen is a versatile chemical element, which can play a role as different energy carriers (heat, electricity and molecules) and as a feedstock material. On Figure 18, the hydrogen chain is presented with possible different upgrades in order to widen the utilization. For example, hydrogen in pure form can be used in all sectors, namely energy storage and power generation, industry (as feedstock and heat), transportation and heating sectors. Different e-fuels can be synthesised as a next step of Power-to-X system. As a result, different new chemicals can be produced carbon-free (some of them are ammonia, methane and methanol), which could be used further in different sectors, where electrification is impossible.

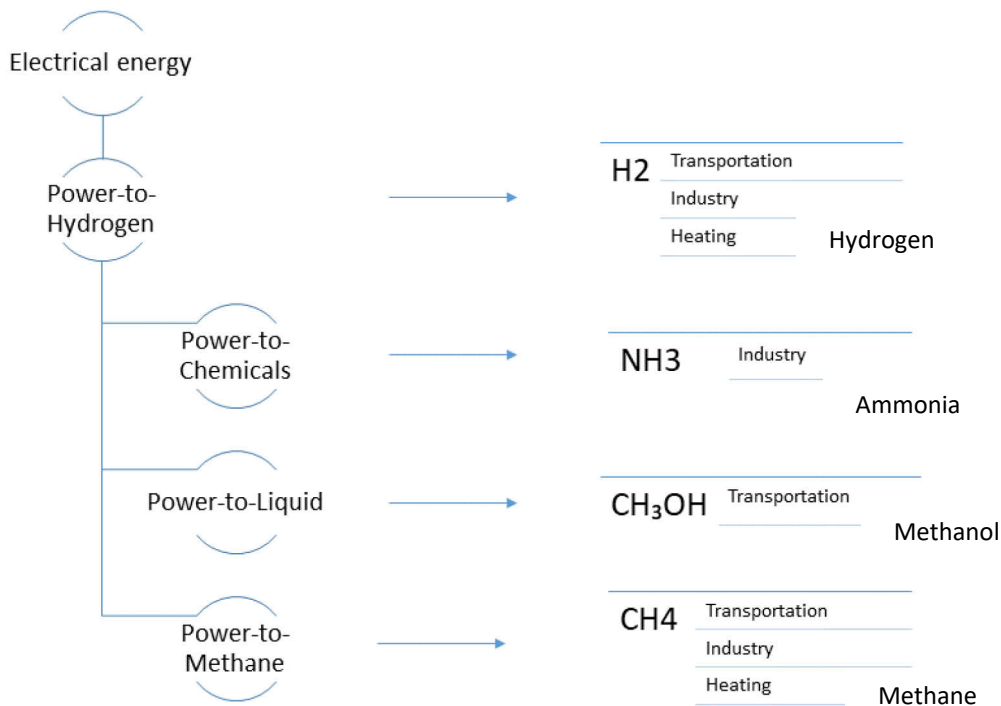


Figure 18. Power-to-X concept with sectoral applications. Self-designed. Based on (Drees et al., 2020)

Hydrogen and the decarbonisation of the power and storage sector

In the power sector hydrogen can play an important role as an energy storage and energy back-up system for the unstable renewable energy generation. During the times with low demand, the extra electricity generated by the wind turbines or PV installations can be chemically stored in a form of compressed hydrogen, and during the peak demand times the stored hydrogen can be converted back to the electricity via fuel cells. The round-trip efficiency remains limited at 35–50%. (Lund et al., 2015) Another application in the power sector of hydrogen can be used in isolated from electricity grid territories. Power-to-hydrogen in these cases can provide power supply by off-grid and back-up electricity generation. This option could save investments in the transmission and distribution grids construction and operation.

Project H2FUTURE (A European Flagship Power-to-X Project) can be used as an example for the power sector case. The project combines together energy supply companies, technological suppliers, and academic partners to create 6 MW electrolyser with a production rate of 1200 m³ of green hydrogen per hour. H2FUTURE main target is to produce green hydrogen for the power production and balance the energy system. (World Energy Council, 2019)

Hydrogen and the decarbonisation of the industrial sector

In the industrial sector, hydrogen is used as a feedstock material. Usually it is grey hydrogen from the Steam Methane Reforming process, which results in large amounts of CO₂ emissions (globally 3% of industrial GHG). (Soltani et al., 2014) By replacing grey with green hydrogen, big contributions to the reduction of the GHG emissions will be achieved. On Figure 19 different industries are presented that use hydrogen as a feedstock, the main are oil refining, ammonia production for different fertilizers, steel processing etc.

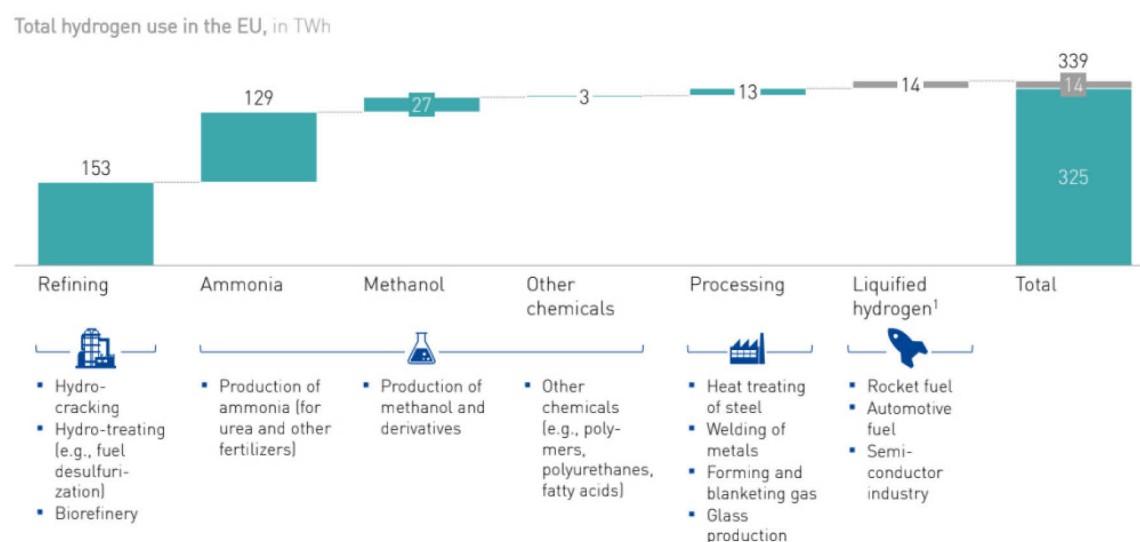


Figure 19. Hydrogen as a feedstock material for different industrial purposes. Total hydrogen use in the EU. Source (Europe Hydrogen, 2019)

The industrial giant company, Thyssenkrupp, which originated from Germany, is launching a new strategy to decarbonise different industrial processes. Carbon2Chem project is one of the examples of the company's environmental activities. It is a large project aiming to make the production of fertilizers and steel totally carbon-free via integration of Power-to-X element. The company is also participating in the construction of the world biggest electrolyser with a capacity of 100 MW. (thyssenkrupp, 2020)

Hydrogen and decarbonisation of the transport sector

Hydrogen vehicles today are also benefiting from the technological advances. The mobility sector is a starting point for development of fuel cells and hydrogen. The significant advantage of the fuel cell electric vehicles (FCEV) compared to the battery-powered electric vehicles (BEV) is that it can compete already in technical parameters, not only with BEV, but also with the internal combustion engine (ICE) cars. Hydrogen based cars have zero carbon emissions, are quick in charging (only a couple of minutes) and the performance of the engine is not affected by the climate conditions. In Germany, BEVs will probably have the leading role for

decarbonisation of the transport sector in 2030 (mainly light passenger cars), whereas hydrogen vehicles can substitute major part of public transport and heavy duty vehicles. There is even the potential to decarbonise air and marine transport with the help of hydrogen. (World Energy Council, 2019) Hydrogen trains are already tested and currently in Northern Germany the first hydrogen train fleet on a commercial scale is operating, produced by Alstom, operating instead using the diesel and electrical grids. The investment in the hydrogen train infrastructure is considerably less than for usual diesel trains with an electro grid. (Taibi et al., 2018) Marine transportation also provides positive perspective to replace all fuel oil operated ships with fuel cells. Currently, the medium size boats are being tested. Furthermore, IRENA states in its last report that the International Maritime Organization prognoses, liquid hydrogen to be one of the main instruments for GHG emission reduction target (marine transportation) of 50 % by 2050. (Taibi et al., 2018) In aviation, hydrogen can provide a green revolution as well. For the small propeller-driven aircrafts, fuel cells can be used (German demonstration Project HY4). However, for heavier aircrafts designed for long-distances, e-fuels can be used in order to substitute conventional kerosene. (Taibi et al., 2018)

Germany started development of hydrogen cars by initiating project H2Mobility. Currently 89 fuel stations are operating for approx. 400 fuel cell cars, and by the end of 2020 the number will increase to 100. (H2 Mobility, 2020) However, the chicken-egg problem still exists, which complicates the acceleration in the development of hydrogen vehicles. Governments should support the initial stages of the integration of the hydrogen infrastructure as well as growth of FCEV production simultaneously on economic, technologic and social levels.

Hydrogen and decarbonisation of the building (heating) sector

The heating sector is the most difficult to decarbonise, especially on the residential level. The gradual conversion of the natural gas based system to hydrogen will require a lot of investments and effort. The hydrogen tolerance of the different parts of natural gas infrastructure highly vary, from 2% to 20%. (Taibi et al., 2018) Therefore, the question arises, if the retrofit of the whole system would be the best decision. Another solution is to decarbonise the heating system with the biomethane and synthetic methane, generated from green hydrogen. Switching to a 100% hydrogen heating system would lead to dramatic reduction of the CO₂ emissions in the heating (residential and industrial) sector.

The project H21 located in Northern England, is aiming to show feasibility in the study of retrofitting the national gas pipeline to become 100% hydrogen tolerant in order to decarbonise industrial, commercial and domestic heat in the UK. 3.7 million houses and business are planned for the infrastructural change. Hydrogen from the SMR with CCUS unit is considered in the project. (Northern Gas Networks, 2020)

2.6 Potential exporters of hydrogen

In the study of dena and Navigant (Jensterle, Narita, Piria, Schröder, et al., 2019), the green hydrogen export options are discussed. The hydrogen demand in Germany and in the EU is significantly higher than the theoretical domestic production rates of hydrogen (the land limitation problem). (Gerbert et al., 2018) The research in cooperation with dena, Navigant and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) is highlighting the main opportunities for hydrogen export. (Jensterle, Narita, Piria, Schröder, et al., 2019) In this study of Jensterle *et al.*, only non EU-countries were taken into consideration. On Figure 20, the potential exporters of green hydrogen are presented. The time frames for the green hydrogen development were chosen at the starting date from 2030 (medium term) and from 2050 (long term).

Taking the considerations of both the relatively long-term scenarios (2030 and 2050), the following limitations regarding the choice of the potential exporter country derive. The decisive factors can vary and according to the study of Jensterle *et al.*, they are population density, land quality, economic, social and ecological costs of land use; acceptance of the population and politics, water restrictions (cost of access to water, sustainable availability of water for renewable energy generation and electrolysis). Export restrictions are determining the importance and environmental reliability of the domestic energy requirements, such as decarbonisation of the national energy system must have priority over exports in the countries of origin.

In 2030 Norway and Morocco are the favourable examples of green hydrogen exporters, according to Figure 20 (cheapest electricity price and high readiness of hydrogen integration on political, economic and social levels due to the large solar (Morocco), wind and hydro (Norway) potential and possibility to transport hydrogen via natural gas pipelines. (Wijk et al., 2019) However, the size of the area of the mentioned countries puts limitations on the H₂ export volumes, which makes Morocco unfavourable, compared to other countries (such as Algeria and

Australia) in a long-term run. In a case of Germany, the green hydrogen supply from Morocco can cause more complexities. The green hydrogen would be injected into the European grid and would be impossible to prove that the actual green gas is supplied to Germany and at which amounts. Therefore, Germany would be more secure to rely on direct suppliers of green hydrogen. One of the closest examples could be the Russian Federation, as it is the country with the highest export potential in a long-term. The Russian Federation has the biggest potential of wind energy and water availability. These conditions are significantly higher than the ones on the African continent. (Mitrova et al., 2019) Russia and Germany already has a well-established political and economic relationship, therefore the hydrogen market already has a good foundation to be established.

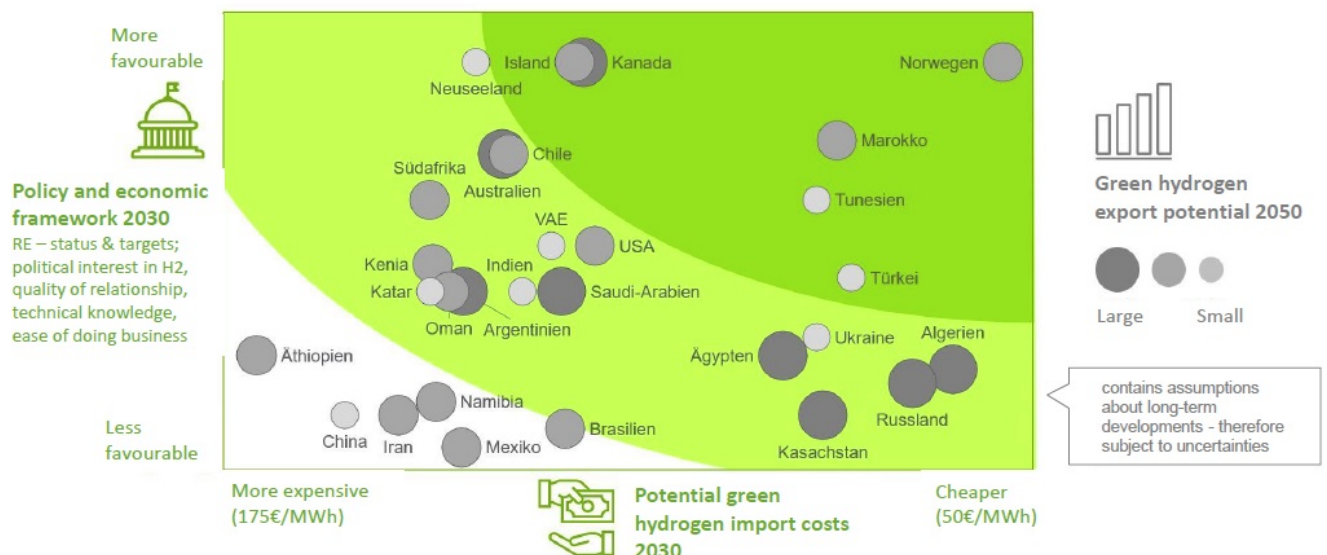


Figure 20. The potential green hydrogen supplying countries for Germany. (Jensterle, Narita, Piria, Schröder, et al., 2019)

Partner countries have to be prepared to meet the particular standards and certifications to initiate the hydrogen trade. In the paper of Jensterle *et al.* two groups of standards were mentioned: technical and sustainable. When designing the *technical standards*, especially on the end-user side, it is often secondary whether the hydrogen used is green. Technical standards can be divided into two categories:

1. Standards that ensure efficient global trade in green hydrogen - international harmonization is essential here (e.g. pressure levels, purity, and pipeline transport).
2. Standards that do not directly affect international trade in green hydrogen - however, international harmonization is often efficient (e.g. safety in fuel cell mobility, materials).

Sustainability standards are intended to ensure that GHG reductions in Germany do not lead to increased emissions in countries of origin, and that the environmental impacts of the hydrogen value chain (creation, conversion, storage, transport, distribution and end-use) are acceptable. The most common criteria used in different certification schemes refer to:

1. Reduction level of life cycle greenhouse gases
2. Water consumption, space requirements
3. Socio-economic and development-policy effects

The following countries could be possible discussion partners. Those are the ones, where the green hydrogen certification schemes have already been introduced or are being discussed, e.g. EU countries (CertifHy; under development), France (AFHYPAC certification scheme; under development), United Kingdom (DECC certification scheme; under development, Japan (certification scheme of Aichi Prefecture). (Jensterle, Narita, Piria, Schröder, et al., 2019)

Key points of Chapter 2.

- 1) Hydrogen is the most abundant and simple molecule in the world. It consists of only one proton and electron and, unlike fossil fuels, does not have any carbon structure, therefore is considered as environmental friendly. Compared to natural gas, the mass of hydrogen gas is 8 times lighter, the volumetric higher heating value is 3 times lower and the gravimetric (HHV) is 3 times higher. These parameters play an important role, when choosing and designing transportation and storage types.
- 2) Colours of hydrogen are used for determining the feedstock and origin of energy for hydrogen production and how carbon-neutral is the resulting product (hydrogen). In this master thesis five colours of H₂ (grey, blue, turquoise, yellow and green) were introduced, but only two (yellow and green) are used in the work. They refer to the process of electrolysis and are different only by the energy source. Yellow hydrogen represents nuclear energy and green hydrogen – renewable energy.
- 3) At the moment the cost of green hydrogen is estimated around 4.7-9.2 €/kg H₂, which is the highest among all the colours. The break-even price of green hydrogen in Germany is estimated at the level of 3 €/kg.
- 4) The concept of Power-to-Gas system (PtG) is established on the four technological steps (presented on Figure 13): the surplus electricity generated from the renewable sources (wind turbines, PV installations), the electrolyser that produces hydrogen and oxygen by dissimilation of water molecules, the methanation option may be added for production of synthetic natural gas (SNG), compression system and storage or injection into the gas grid (either pure hydrogen or mixed with natural gas) systems.
- 5) Demand for green hydrogen in Europe in 2050 is established in the range of 1.050-2.250TWh, depending on level of integration of hydrogen economy. Two works “A Clean Planet for All” by the European Commission and “Hydrogen roadmap 2050” by Hydrogen Europe were taken as the basis for hydrogen demand estimations. The main hydrogen application sectors are industry, heating and transport. German green hydrogen demand is in the range of 80-170 TWh and if including synthetic fuels based on hydrogen, the demand can rise up to 900 TWh, the values were derived from dena study. The main sectors for application are industry and transport.
- 6) Hydrogen is a versatile chemical element, which can play a role as different energy carriers (heat, electricity and molecules) and as a feedstock material. Hydrogen in pure form can be used in all sectors, namely energy storage and power generation, industry (as feedstock and heat), transportation and heating sectors. Different e-fuels can be synthesised as a next step of Power-to-X system. As a result, different new chemicals can be produced carbon-free (some of them are ammonia, methane and methanol), which could be used further in different sectors, where electrification is impossible.
- 7) The hydrogen demand in Germany and in the EU is significantly higher than the theoretical domestic production rates of hydrogen (the land limitation problem).the potential exporters of green hydrogen are Russia, Norway, Algeria, Morocco and Ukraine.

Chapter 3: Russia's potential role in the development of the European hydrogen market

3.1 State of the art of the Russian energy sector and market

The Russian energy system is considered one of the most comprehensive and largest in the world. As an energy autonomous country, the territory of the Russian Federation is rich with all necessary energy sources, such as natural gas, coal, lignite and crude oil. Russia is the third biggest energy producer in the world (after China and the USA). Moreover, since almost half of the energy produced is exported, it contributes significantly to the international energy markets and energy system stabilities (45% of the produced energy is exported, according to the database of Enerdata, Global Annual Statistical Yearbook 2019). Apart from that, Russia holds a top five leading position for each exported type of fossil fuel. Also in terms of electricity consumption, Russia is in the fourth position, after China, the USA and India. In 2018, electricity generation in the Russian Federation amounted to 1128 TWh (Table 11). The energy produced in Russia contributes a quarter of national GDP, which is 3% of the world's total GDP. (IRENA, 2017; Mitrova & Yermakov, 2019)

In Table 13 is shown the state of the Russian energy system in 2018 in terms of the production, consumption and trade of the fossil fuel resources and energy in total. Besides that, the change compared to 2014 is shown as a percentage difference (green and red colours indicated increase and decrease respectively). 2014 is known as the year of the global oil crisis due to the fall of oil prices, multiple sanctions, limiting international trade with Russia and hampering economic growth within the country, which caused the deepest drop of the Russian economy and social well-being in the last decade. In 2018 fuel exports in total increased by 18%, with a major expansion of the natural gas export capacities of 46% from 188 bcm to 274 bcm. Export of solid fossil fuel also raised by 28,5%. Only the market of refined oil products shows light decrease by 4% in 2018 compared to 2014. The progression in the revenues from the fossil fuel trade took place after the agreement between OPEC countries and Russia, by limiting the crude oil production and by shifting targets from the competition for the largest share in the market, to maximizing the profits in the long term strategy. (Enerdata, 2019)

Table 13. Overview of the Russian energy market, level of exports in 2018 and compared to 2014. Adapted from (Enerdata, 2019)

	Crude Oil (Mt)		Oil products (Mt)		Natural gas (bcm)		Coal, lignite (Mt)		Electricity (TWh)		Total Energy (Mtoe)	
	2018	2014	2018	2014	2018	2014	2018	2014	2018	2014	2018	2014
Production	556	5,70%	276	-2,47%	741	14,53%	412	23,35%	1128	6,02%	1492	13,12%
Consumption			147	-3,92%	505	8,60%	234	17,59%	929	5,93%	800	12,83%
% from Production			53,26%	-	68,15%	-	56,80%	-	82,36%	-	53,62%	-
Trade	-258,2	16,31%	-110,8	-3,65%	-273,9	45,69%	-168,3	28,47%	-12	49,07%	-673	17,86%
% from Production	46,44%		40,14%	-	36,96%	-	40,85%	-	1,06%	-	45,11%	-

The Natural gas market faces positive changes and expansion of the production as never before. The latest strategy until 2035 released by the Minenergo (the Energy Ministry of Russia) in the autumn of 2019, shows development of natural gas markets (both European and Far East) and establishment of the liquefied natural gas (LNG) market. Gazprom is a leader in the pipeline export of natural gas and according to the strategy, the production will rise from 727,6 bcm in 2018 to 907-983 bcm in 2035. The LNG market leader is Novatek with an increase in production from 26.9 bcm in 2018 to 110-127 bcm by 2035. (Mitrova & Yermakov, 2019) Gazprom is aiming to hold the share of the European natural gas export. As the natural gas demand in the next decade is projected to increase in Europe due to decarbonisation pressure targets, it is a signal for Gazprom and Novatek to react fast on the growing demand and expand the production capacities. Moreover, the recent projects of Gazprom “Nord Stream 1 and 2”, as well as “Turkish Stream” are showing the readiness of the supplier to provide higher volumes of natural gas in the future.

Installed power generation capacity mix

In terms of installed capacity, Russia ranks fifth, after Japan, in addition to the previously mentioned countries. According to the statistical data provided by the energy ministry of Russia, in the beginning of 2018, the installed capacity corresponded in 2017 to 272 GW (240 GW in Unified Energy System of Russia (UES) + 32 GW in isolated areas), see Figure 21. Thermal power plants (gas, coal and oil) have the majority of the capacity, representing 70% of the total, followed by hydro (20%), nuclear (10%) and renewable wind and solar (0,3%) capacities installed. (Lohse *et al.*, 2018) The majority of the installed capacity was built in Soviet times, therefore requires deep modernisation. As a measure to increase efficiency and retrofit the aging power plants, the “Energy Efficiency and Development of the Energy Sector” program and

the program for building new generating capacities were initiated by the government in 2013-2020. However, due to the stable energy demand in Russian energy system and slow decommissioning of the old inefficient capacities, the overcapacity in the energy market exceeded 20 GW in the winter term and 30 GW in the summer term. As a result, the construction of the modern efficient power plants slowed down. (Chukanov et al., 2017)

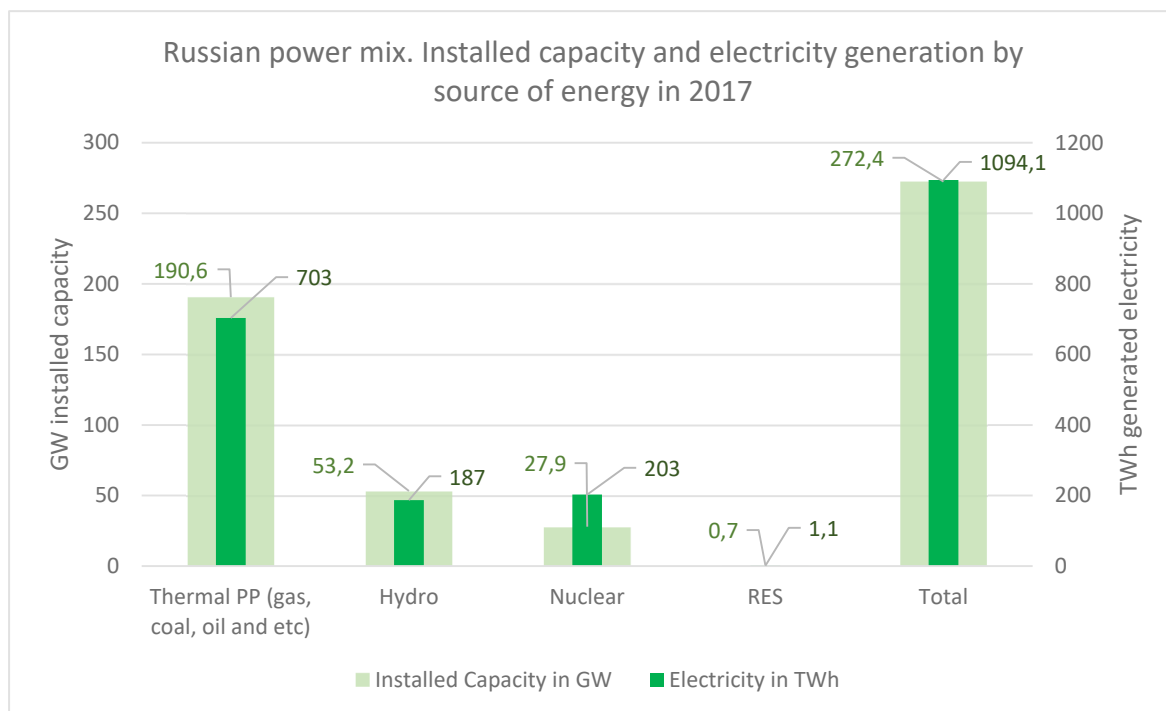


Figure 21. Russian power mix in 2017 (with installed capacity and electricity generation by energy source). Adapted from (Lohse et al., 2018)

In terms of the electricity production, thermal power plants operating on natural gas occupy almost half of the total production, followed by large hydro, coal and nuclear power plants (Figure 22). In most cases thermal power plants are combined heat and power type (CHP), resulting in a better efficiency, up to 70%. More than a third of the total energy, in terms of heat and electricity, is provided by CHP plants, covering this way the base and medium load. However, the CHP-units are outdated and the efficiency factor drops significantly. This leads to different problems, as in winter time it is incapable to cover the peak demand and, therefore the flexible operation of hydro, gas and biomass power plants is initiated. (Chukanov et al., 2017)

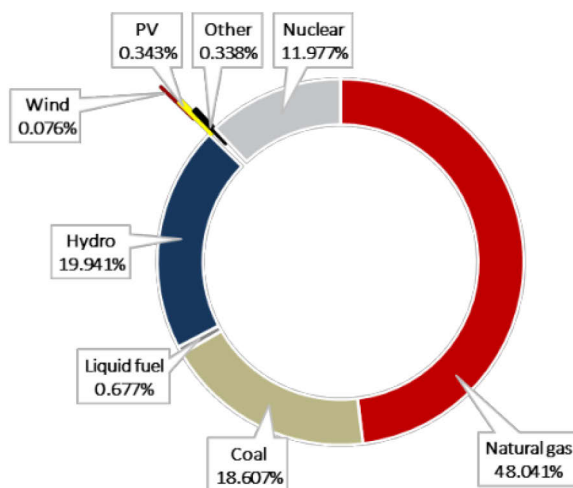


Figure 22. Installed capacity for electricity generation in Russia in 2018. (Lohse et al., 2018)

Russian energy market design

The Russian energy market has undergone manifold modifications and restructuring since the 1990s. Today's electricity market represents a complex, liberalized system with wholesale and retail markets. The main participants in the wholesale market are the privatised energy companies from the 2000s. Part of the companies' shares are still owned by the state. Electricity can be purchased via wholesale markets in four different ways: regulated bilateral agreements; unregulated bilateral agreements (free pricing), the day-ahead market (free pricing), and the balancing market. Participants of the wholesale market are obliged to participate in the retail market by selling particular volumes of electricity. Capacity wholesale market was initiated to provide secure and stable electricity by ensuring that capacity of each generator will be maintained. The market is operating with the contracts for running capacity with maximum 10 years' time slots. The balancing market is a matter of power system operators. The Russian energy system is a nodal system (8400 nodes), at which the market reacts to any uncertainty of the supply, imbalances or unplanned shortage. (Lohse et al., 2018)

3.2 Energy strategy 2035: echoes of Western decarbonisation in Russia

2019 was an important year for the development of the Russian energy system. In the September of 2019 Russia ratified the Paris Agreement. Thus, in light of the commitments made by Russia under the Paris Agreement, the development of low-carbon energy sources, including renewable energy sources, is becoming one of the priority tasks.

According to IEA, Russia contributes 5% or 1438,6 Mt of the global carbon dioxide emissions and is ranking 4th place in the list of the main CO₂ emitters after China, the USA and India. (IEA, 2019)

However, the question of decarbonisation is not on the top of the agenda of the Russian energy strategy, as it is for European countries. It's difficult to compare Russia with other countries in the Paris Agreement due to different factors, such as the area of the territory, its population density, the density of electricity production, presence of the heavy industries, power mix, dependence on fossil fuels, economic stability of the country and many others. Nevertheless, compared to 1990 Russia achieved a cut of CO₂ production by 40% already by 2000, ahead of the 2020 deadline, as a result of the collapse of the Soviet Union and not intensive decarbonisation policies.

To go into more details, the majority of CO₂ emissions and other cancerogenic pollutants (NO_x, SO_x and PM) are originated from industrial activities, transportation and waste. The majority of the GHG-emissions are a result of the energy generated for industry and during its technological processes. According to IRENA, industries in Russia are the largest consumers of electricity (53%), mainly based on coal and less on natural gas. (IRENA, 2017) The most polluted cities in Russia are industrial cities with a population up to 100 thousand people, such as Norilsk, Krasnoyarsk and Magnitogorsk. These places have been announced as “ecologic catastrophe zones” by the Ministry of Natural Resources of Russia. (Минприроды России, 2018) Even though the Russian territory is rich with endless forests, the CO₂ emissions cannot be totally “naturally sunk”. Figure 23 represents the allocation of the main CO₂ emission sources and the last column (Negative figures refer to sinks, or absorption of greenhouse gases from the atmosphere). (Statista, 2017)

The Electricity sector in Russia has one of the lowest CO₂ emissions in the world. The share of natural gas power plants (PP), hydro PP and nuclear PP in total represents 80% versus 18% of electricity generated by coal PP (Figure 22). Therefore, the low or zero carbon emitting power generation sources provide a lower carbon footprint compared to leading decarbonised countries.

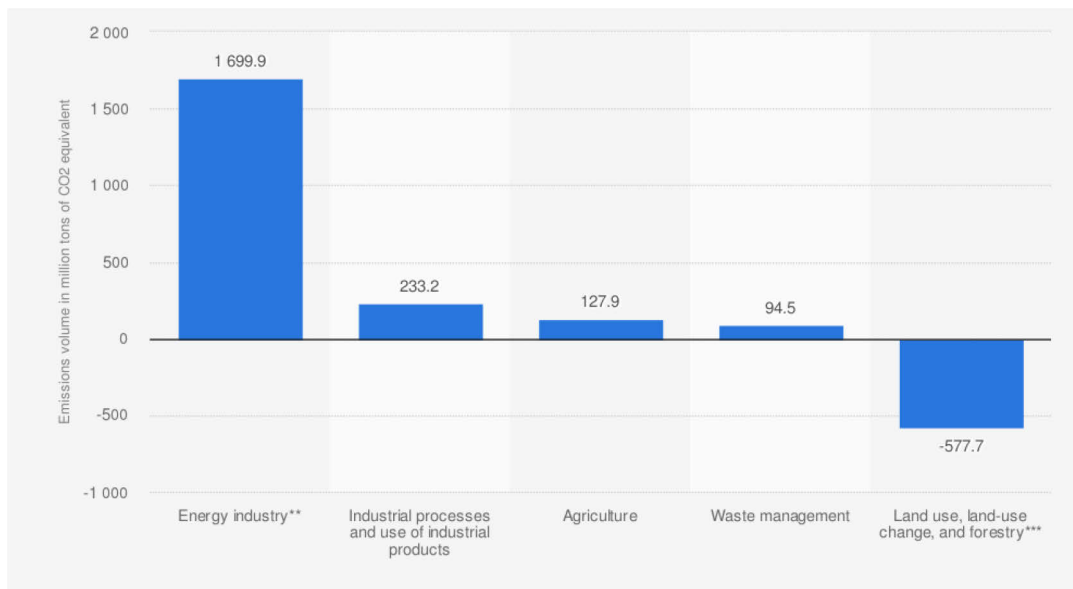


Figure 23. Greenhouse gas emissions in Russia in 2017, by source sector. (Statista, 2017)

Energy Strategy 2035 (ES-2035) and development of the renewable energy in Russia

One of the key goals of the energy strategy is to reduce the energy intensity, as well as the emissions and to develop renewable energy and energy storage systems. The strategy highlights the following achievements in the field of renewable energy (RE) in Russia:

- The development of electricity based on renewable energy sources (hereinafter - RES) has been developed. The installed capacity of renewable energy (excluding large hydro PP) in the UES of Russia in 2018 reached 1.018 GW (PVs - 0.834 GW, wind turbines - 0.184 GW).
- The mechanism of state support for the use of renewable energy sources in the wholesale electricity and capacity market of Russia through capacity supply agreements has made it possible to increase the investment attractiveness of the renewable energy industry and to create its own production of renewable energy equipment corresponding to the world level - solar energy and wind energy.
- Moreover, quotas for support of the renewable energy facilities were introduced by the Russian government for the period 2025-2035. The wind farms have the majority of the support 55,5%, followed by solar energy companies 37% and micro/small hydropower installations 7,5%. (Eurasia Network, 2019)

Nevertheless, the authors of the ES-2035 state the main obstacle of using renewable energy sources – their lack of economic competitiveness in relation to other electricity generation technologies. (Ministry of Energy of the Russian Federation, 2019)

Russia is a country with the largest wind potential in the world – valued at 17.1 thousand TWh, which is 16 times higher than the country's total energy production in 2018. (Mitrova et al., 2019) However, in the power mix wind energy does not exceed 1 %. By the end of 2019 the wind capacity installed in Russia represented 190,54 MW (564 wind turbines), which compared to the German wind market of 60 GW (third largest in the world), it is only a drop in the ocean. Nevertheless this is only the start of Russia in the renewable energy industry. (Russian Association of Wind Industry & Skolkovo Energy Center, 2020) According to the latest data, the Government specified the parameters of a future program to support green generation. The ultimate value of specific capital costs in 2019 for a wind farm is proposed to be set at around 85 thousand rubles/kW (approx. € 1060/kW), for a solar farm - 75 thousand rubles/kW (approx. € 935/kW), which goes in line with the global cost levels. In 2035 the capital costs are expected to fall to 42,54 thousand rubles/kW (approx. € 520/kW) and 17,651 thousand rubles/kW (approx. € 215/kW) respectively. (Russian Association of Wind Industry & Skolkovo Energy Center, 2020) Figure 24 represents the yearly added capacity of wind turbines from 2015-2024, with the overall installed capacity being 3375,84 MW.

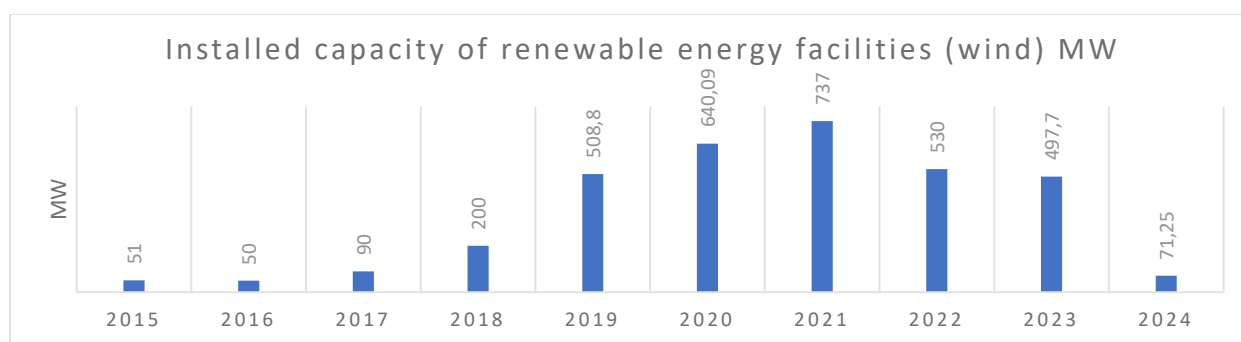


Figure 24. New installed capacity of renewable energy facilities (wind) based on the results of competitive selection power wind generators starting in each year from 2015 to 2024, in MW. adapted from (Russian Association of Wind Industry & Skolkovo Energy Center, 2020)

3.3 Potential role of hydrogen market in Russia

According to the ES-2035, by 2035-2040 the Russian energy sector should reflect the changes of the other international energy systems due to decarbonisation and innovation growth. It will require accelerated transition to a more flexible, efficient and sustainable domestic energy system. In order to respond to these targets, the structural diversification of the Russian energy system, which is currently based mainly on fossil fuels, will have to be adapted with renewable and hydrogen energy, increase of electrification in different sectors, increase of the use of natural gas, further development of centralised and decentralised energy systems, establishment of an export market of Russian technology, equipment and service. (Ministry of Energy of the Russian Federation, 2019)

Variable renewable sources such as wind turbines or PVs are usually accompanied by energy storage technologies, most common of which are batteries and Power-to-Gas systems (when focusing on the minimization of the carbon content). In the Energy strategy of the Russian Federation 2035, hydrogen is mentioned not only as a seasonal/long-term storage option, but rather as an innovative tool for decarbonisation of different sectors (transport and industry) and as a potential export commodity. According to expert estimates, hydrogen production only at existing Russian generating facilities can allow Russia to establish hydrogen exports to a significant share of the global hydrogen fuel market until 2035. In numbers the annual target export of hydrogen is 2 mln tons in 2035. (Ministry of Energy of the Russian Federation, 2019)

For the realisation of the hydrogen target above and the achievement of a placement between the global leading exporters of hydrogen in 2035, the following regulative key measures are highlighted in the ES-2035:

- implementation of government support measures for establishment of the hydrogen and e-fuels infrastructure
- legislative support for the production of hydrogen using excess capacity of the electric power industry (legislative regulation of the procedure for using excess capacity for hydrogen production)
- scaling up the production of different sources: natural gas, the RES and nuclear energy
- development of domestic low-carbon technologies for hydrogen production (SMR, methane pyrolysis, electrolysis, etc.,)
- localisation of the foreign experience in hydrogen technologies
- stimulating domestic demand for hydrogen fuel cells in Russian transport, as well as the use of hydrogen and e-fuels as energy storage to increase the efficiency of centralised energy supply systems

- international cooperation in the development of hydrogen energy and access to foreign markets

(Ministry of Energy of the Russian Federation, 2019)

The energy strategy 2035 shows the interest of Russia to respond on the decarbonisation challenges of the globe and provide own services to the countries with lower energy potential. Nevertheless, to achieve the following ambitious targets of establishing a new hydrogen economy, a significant amount of changes in the energy system, regulatory bodies, support schemes, safety regulations, academia and society have to be completed.

The starting point of the development can be the transport sector. In the transportation sector, the development of the FCEV has been carrying on for over a decade. In Yekaterinburg in 2015 the hydrogen bus project with a pilot refuelling station was proposed for testing in city conditions. (Mitrova et al., 2019) In 2019 on the streets of Saint-Petersburg, a hydrogen fuelled tram was tested. The results confirmed the effectiveness and viability of this type of transport. The project is based on the engineering design of St. Petersburg engineers from Krylov State Scientific Center, and its successful implementation has confirmed the position of St. Petersburg as a scientific and technical center of the country. The use of fuel cell powered trams and trolleybuses will make it possible to abandon the construction of an expensive contact network and traction substations and improve the ecological quality of the air in the city. (Administration of St.Petersburg, 2019) The research base on the fuel cell is well established and in different regions test laboratories are working on the development of the FCEV, such as The Institute for the Problems of Chemical Physics Institute at the Russian Academy of Sciences (hydrogen-oxygen proton exchange membrane fuel cells), the Autonomous Energy Centre of the Moscow Institute of Physics and Technology (solid oxide fuel cells) and the Institute of High-Temperature Electrochemistry of the Ural Branch of the Academy of Sciences (solid oxide fuel cells). (Mitrova et al., 2019)

The existence and development of national standards in the field of hydrogen technologies and fuel cells, identical to the international ISO and IEC standards, will allow the country's enterprises to be integrated into the international hydrogen energy market on an equal footing in the very near future stated A. Ramensky, the President of the National Association of Hydrogen Energy in the Crocus Expo exhibition Comtrans 2019. Currently more than 30 national and interstate standards in the Russian Federation are in force. These standards cover the entire spectrum of production, storage and use of hydrogen in various types of vehicles, including the

technology of refueling vehicles with hydrogen fuel. (National Association for Hydrogen Energy (NAHE), 2019)

3.4 Possible domestic green hydrogen generation methods (renewable electricity-based electrolysis vs. nuclear/hydro based electrolysis)

The Federal North-western region of the Russian Federation was chosen as the potential strategic hydrogen sector with a focus on export to German and European hydrogen markets. On Figure 25, the region is marked with orange. The strategic geographic location of the region is one of the main benefits, as it provides a direct access to Germany via the Baltic Sea. Moreover, the North-western region of Russia shares borders with Finland, Estonia, Latvia, Lithuania, Belarus and Poland. One of the largest harbours in Russia, which takes the major part of all international sea cargos, is located in Saint-Petersburg, the administrative centre of the region, where the 70% of the population is concentrated. Apart from being engineering and industrial centre of the region it also has a strong academic establishment (around 20% of the whole country). Therefore, perfectly suited for innovative projects.

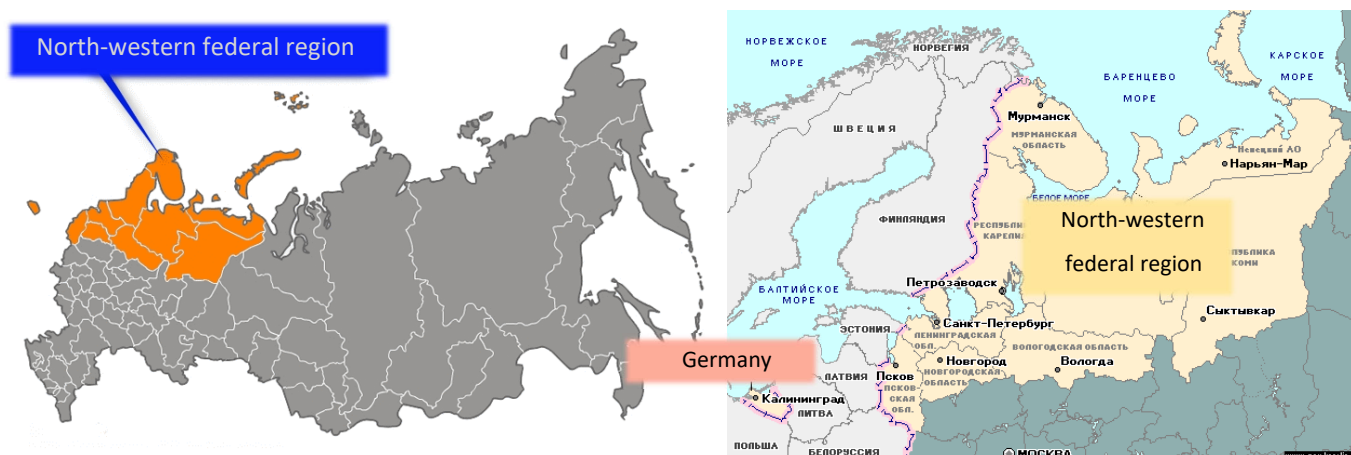


Figure 25. Map of Russian Federation, North-western federal region.

Due to the lack of the region's resources, the role of manufacturing is crucial. The leading position is occupied by engineering, especially industries focused on highly qualified labour resources (radio electronics, instrumentation, electrical engineering), and industries that have developed during the formation of the country's economic complex (shipbuilding, car building, power engineering (nuclear energy), machine tools and other similar industries). Fertiliser

enterprises are located in Veliky Novgorod (nitrogen and complex substances) and Kingisepp (phosphoric and complex substances).

According to data from the Ministry of Energy of the Russian Federation, the regional energy system has in total 24,5 GW of the installed capacity (status on the 1st of January 2020). The majority of energy capacities are thermal power plants (63,6%), operated mainly on natural gas, followed by nuclear power plants (24,3%), hydro (12%) and wind energy (0,02%). (Ministry of Energy of the Russian Federation, 2020b) The fuels for thermal and nuclear PP are transported from the eastern regions of Russia, whereas the local hydro potential is high. Considerable quantities of water resources are concentrated in the North-West: 7000 lakes (Ladoga, Onega, Chudskoe, Ilmen), a dense river network (Neva, Volkhov, Lovat). (Geography of Russia, 2017) The overall picture of the region provides a good environment for the introduction of the hydrogen economy. Important factors are the development status of the North-western region, geographic location, the long history of operation of industrial facilities, the high qualified labour force and the well-established research centres, which could accelerate and simplify the beginning stages of hydrogen development and integration into the energy complex of Russia.

In this thesis the focus is put on the production of hydrogen by means of electrolyser, so-called green or yellow hydrogen depending on the energy source. Blue hydrogen has high potential on the hydrogen market in Russia, however is not included in the scope of this work, as the backbone of the technology is natural gas and is leading to CO₂ emissions. Therefore, three energy sources (nuclear, hydro and wind) are chosen for the analysis of the levelised cost of hydrogen (LCOH). The energy sources are divided according to whether investments into new capacities are needed or not. Nuclear and hydro power plants are classified as existing facilities, whereas wind parks are considered as a potential energy source, thus capital costs are necessary.

Potential estimation of nuclear and hydro based hydrogen

As mentioned earlier, the Russian energy system has significant amount of unutilised installed capacities due to low regional demand, which decreases the efficiency of the system. According to the Ministry of energy of the Russian Federation, in the North-western region nuclear power plants had a capacity factor of 74,1% and hydro power plants 46,7% in 2019. (Ministry of Energy of the Russian Federation, 2020b) The low-carbon electricity production can be a platform for the establishment of hydrogen production via electrolysis in the region. The Infrastructure

Center EnergyNet has released an expert analytical report on the hydrogen potential in Russia, where was stated, that by unlocking capacities of nuclear and hydro power plants, the overall capacity factor can increase by 5-7% compared to the levels of 2017. (Infrastructure Center EnergyNet, 2018) As an example, two nuclear power plants (NPP) in the North-western region Kolskay NPP and Leningradskay NPP with an increased capacity factor from 70% to 93% could provide already in 2025-2030 approximately 160 thousands ton of H₂ per year. This could be more than sufficient to supply European hydrogen pilot projects. The overall availability in the nearest future production capacity of hydrogen in the North-western region can roughly be estimated at 430 thousand tons of hydrogen per anum when utilizing the electricity generation facilities. (Infrastructure Center EnergyNet, 2018)

Potential estimation of wind-based hydrogen (surplus electricity)

The wind based hydrogen in Russia is facing manifold barriers. Due to a low number of operating wind capacities and small experience in this industry in general, wind-hydrogen systems can be challenging. Wind and solar energy have just recently started to gain momentum in the country, and is still not clear how far the developments will lead. Nevertheless, wind-based hydrogen has been already considered as the green and cheap alternative for the energy supply to remote and isolated territories of Russia, located on the north coast of the Arctic Ocean. Such territories have great wind potential (onshore and offshore). Currently diesel generators are the main sources of energy in such remote and isolated areas. However, due to the complicated logistics of the fuel and the severe climate conditions, the costs rise significantly, representing 1-1,3 €/l diesel. The wind-hydrogen symbiosis can allow the creation of island systems, thereby contributing not only to the establishment of energy independence in the region, but also to the environmental protection as well. According to calculations of the authors from EnergyNet, the cost of the hydrogen system will be by a quarter lower than that of the conventional system. (Infrastructure Center EnergyNet, 2018) The pilot project is coordinated by The Moscow Institute of Physics and Technology (MIPT) with the support of the Russian government, National Technology Initiative and foreign partners. The idea is to construct a completely autonomous International Arctic Station in polar territories of Ural (the Land of Hope). The pilot-project is designed for electricity production from renewables combined with a hydrogen storage system instead of diesel. The start of the tests are scheduled in 2022. (FuelCellWorks, 2020)

The Russian Association of Wind Industry stated that 351 MW of wind parks are currently under construction in Murmanskaja oblast located in the north of the North-western. The wind capacities to be installed are owned by two companies: 150 MW by Rosnano and Fortum and 201 MW by Enel Russia. (Russian Association of Wind Industry & Skolkovo Energy Center, 2020) These generation capacities can be a basis for the first pilot plants of the renewable hydrogen in Russia

3.5 Russian potential export routes of Hydrogen

Hydrogen logistics is variable and depends on the amounts of hydrogen to deliver, form of hydrogen (gas/liquid), distance, geographical landscape and other different factors. Small hydrogen plants are usually decentralised and can be located near the source of energy and in some cases coupled together, for example a wind park, therefore, minimizing costs for the grid infrastructure. In such local case the transportation via trucks or small pipeline system can be suitable. The large centralised hydrogen facilities, aimed for production of hydrogen in thousand tons per year, are suggested to be located near by the delivery facility such as gas network or freight harbor. Such logistics are usually situated on higher levels – national or international. (IRENA, 2019) For the development of an international market and, therefore, in the logistics of hydrogen, the role of the internal hydrogen market of the producer country play does not have significant effect and can be absent. Such examples are Australia supplying hydrogen to Japan and Norway to Asian countries. (IRENA, 2019) Russia can become a hydrogen supplier for Germany and in this case, following the experience from the above examples, the international maritime transportation could become the most preferable delivery option. Pipelines could be also an interesting alternative for the shipment of hydrogen in liquid forms, however there are some obstacles, which will be mentioned later in this sub-chapter. Because of these obstacles, in this master thesis, for the case study Russian-German hydrogen market only the maritime transportation is assumed.

Liquid transportation of hydrogen

The maritime transportation of hydrogen can be considered similar to the transportation of natural gas in the liquid state. Due to its low volumetric density and high gravimetric density, hydrogen needs more space to be stored. Therefore, liquefaction of hydrogen or coupling with different chemical compounds are the necessary conditions. In different studies (Aziz et al.,

2019; IRENA, 2019; Wijayanta et al., 2019) three options of transportation of hydrogen are standing out: liquid hydrogen (LH₂), ammonia (NH₃), and liquid organic hydrogen compounds (LOHC) (in most cases methylcyclohexane (MCH)). These hydrogen storage technologies attract a lot of attention for several reasons: better storage capacity, carbon-free emissions, improved economic feasibility and state of development of the technology itself and its regulations. (Wijayanta et al., 2019) Important criteria for choosing the liquid hydrogen storage are the high volumetric and gravimetric density, the safety measures, the profitability, the high reversibility and the minimal environmental impact. On Figure 26, the authors Wijayanta *et al.* compare the storage capacity of the technologies LH₂, MCH and NH₃ and their gravimetric and volumetric densities. The highest gravimetric density belongs to liquid hydrogen, followed by NH₃ and MCH. Regarding the volumetric density of hydrogen, however, ammonia transportation method is leading, followed by liquid hydrogen and liquid organic hydrogen compounds. The above mentioned states, that MCH method requires the largest tanks to store hydrogen during the transportation or static storage compared to other two storage alternatives.

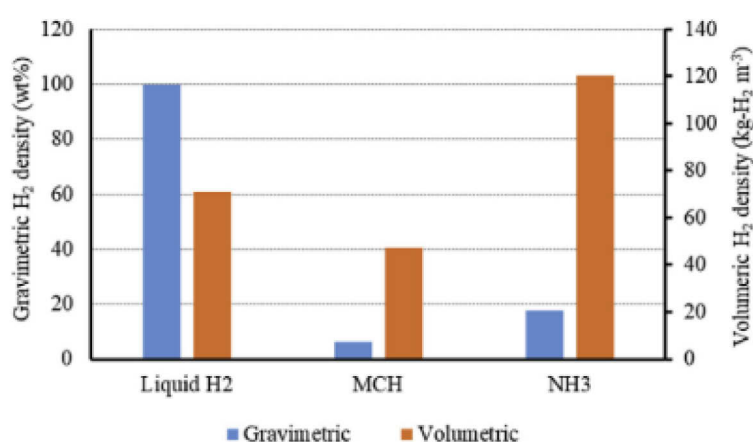


Figure 26. Comparison of gravimetric and volumetric H₂ densities of LH₂, MCH, and NH₃. Source (Wijayanta et al., 2019)

To understand better the comparative overview of the features of each liquid hydrogen storage method, the best way would be to look into the processes in more details.

Liquid hydrogen

The first storage method, liquid hydrogen, involves several steps represented on Figure 27: liquefaction, storage, transportation and regasification of hydrogen. The process is similar to the liquefaction of natural gas (LNG). During the liquefaction stage hydrogen is refrigerated to

its critical point of liquid state - to the temperature of $-252\text{ }^{\circ}\text{C}$ and pressure of $1,3\text{ MPa}$, which is drastically lower than for LNG ($-160\text{ }^{\circ}\text{C}$). (Godula-Jopek et al., 2012) The authors Wijayanta *et al.* refer to the patent of the Japanese Industrial company Kawasaki Heavy Industries, who are starting to transport hydrogen in liquid state from Australia to Japan. (Kamiya et al., 2015) In comparison to natural gas liquefaction, hydrogen requires significantly more energy input, different safety regulations and stricter insulation of all components. The authors Kamiya et al. mention that hydrogen production and liquefaction facilities can be coupled together and, thus, overall efficiency can be improved or the liquefaction facility can be placed in the port area and hydrogen can be delivered there via pipeline or trucks. However, the second option faces many obstacles, such as the high expenditures for the construction, operation and regulation to place the infrastructure. One of the main obstacles of the hydrogen liquefaction is the intense energy consumption, which corresponds to the one-third of the total hydrogen supply. The authors state that the efficiency of the liquefaction stage should not be less than 40% and with further research and development the losses can be minimised. (Wijayanta et al., 2019) For the storage and transportation of LH₂ the excellent insulation technology, such as thermal insulation is recommended. (Kamiya et al., 2015) During the transportation of liquid hydrogen some losses appear too, represented by the so called boil-off parameter. The losses are caused due to readjusting internal pressure of the vessels, when it's reaching its maximum point. Usually the boil-off point losses corresponds to 0,2-0,3% of the stored amount of H₂ per day. However, the released hydrogen can be utilised as fuel for the ship itself to save the losses. (Wijayanta et al., 2019) The last stage - regasification is where the hydrogen is brought up back to ambient conditions and the cold can be recovered to increase efficiency of the system. Usually Rankine and Brayton cycles are applied. Regasification combined with utilization (power generation with H₂ turbines) leads to the best efficiency, which can reach a theoretical maximum of 74%. One of the benefits of the liquid hydrogen storage and transportation is that hydrogen is not mixed with any other compounds, therefore providing 98% purity, suitable for direct utilization in the fuel cells and hydrogen turbines with no need of purification step. (Wijayanta et al., 2019)

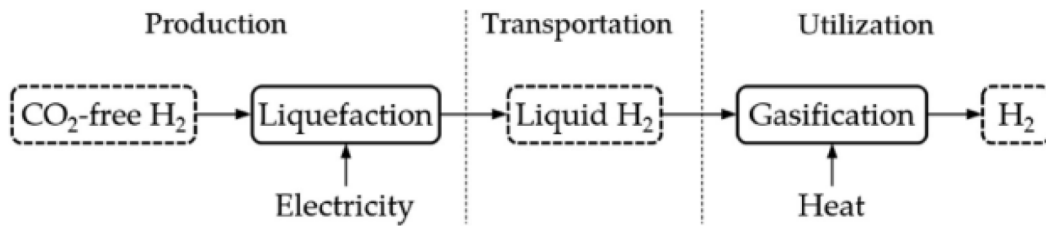


Figure 27. H₂ storage/transportation through liquid H₂ (Wijayanta et al., 2019)

Toluene-MCH as LOHC

In this chemical storage the molecule of hydrogen is covalently bonded to the molecule of the liquid organic compound via hydrogenation. Further, after transportation, hydrogen can be released via process of dehydrogenation. On Figure 28 the method's steps are illustrated. Among all LOHCs, toluene-MCH is chosen as the most effective chemical storage compound. (Preuster et al., 2018) Toluene-MCH is considered as the optimum LOHC, thanks to the wide temperature range of operation during storage and transportation, the high stability rate and the excellent reversibility. Moreover, toluene-MCH has been already tested in 1990s in the Euro-Quebec Hydro-Hydrogen project (Drolet et al., 1996). As a result MCH as a hydrogen carrier was accepted by the public and the safety and technical regulations for storage and transportation are already existing. The first stage is hydrogenation where toluene is reacting with hydrogen with a presence of a catalyst at temperatures 180-300 °C and pressure of 2 atmosphere. The reaction is exothermic, therefore, the released heat can be utilised in the other H₂ related processes to improve efficiency. MCH is then cooled down to its liquid state (at the ambient conditions) and transported in normal gasoline tanker ships. The advantage is that MCH has been already tested and is considered suitable for long-distance transportation. (Wijayanta et al., 2019) The dehydration step is the most problematic, as is very energy consuming. The best scenario for this stage is to combine the dehydration unit with some industrial processes, where lots of waste heat is present. To receive as an end product high quality hydrogen, a purification unit, for example, pressure-swing adsorption or different membranes, is essential. The main disadvantage is that toluene-MCH requires large transportation containers, significantly larger compared to liquid hydrogen and ammonia.

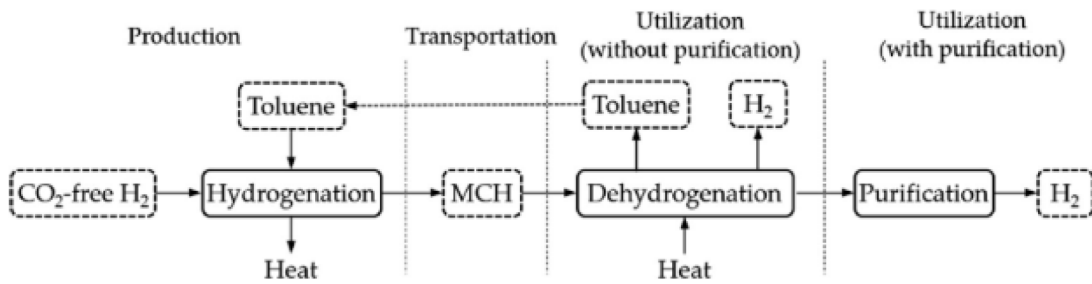


Figure 28. H₂ storage/transportation through LOCH (MCH). (Wijayanta et al., 2019)

Ammonia

Ammonia is a well-known chemical compound, produced globally on a large scale. Therefore, it provides a weighted benefit as the infrastructure and regulations of the transportation and storage are developed and practiced for decades. Ammonia is used as a feedstock material for production of chemical materials and fertilizers, as well as a reductant in combustion furnaces to minimize the NO_x emissions. The technology consists of similar steps as the two alternatives described before: synthesis of NH₃ from H₂ and captured from air N₂, storage, transportation, decomposition, purification and utilization or direct usage of ammonia. This chemical storage shows excellent characteristics in performance, such as hydrogen stability and safety, resistance to temperature ranges and low reaction speed in combustion. NH₃ has the highest volumetric capacity to store hydrogen, therefore it shows the highest volumetric density. (Figure 29) However, the downsides of NH₃ are its high toxicity, corrosivity and a suffocating odour, which requires more safety measures during handling and transportation to avoid leakage. The synthesis of NH₃ is achieved via the Haber-Bosch reaction, where nitrogen is combined artificially with hydrogen molecule at the range of temperatures 300-600 °C and at a relatively high operating pressure of 15-30 MPa with high energy input. (Wijayanta et al., 2019) Liquid ammonia is stored at low pressure, around 0,87 MPa and ambient temperature. For liquefied ammonia LNG tankers can be utilized, therefore, the state of readiness of the technology on commercial level is already developed and implemented. As was mentioned earlier, ammonia is a feedstock for chemical industries and as the first option, can be utilized directly. The second option is to decompose hydrogen. Decomposition processes are usually either electrolysis or

thermal decomposition, which are expensive as they require high temperatures (>800 °C) for operation.

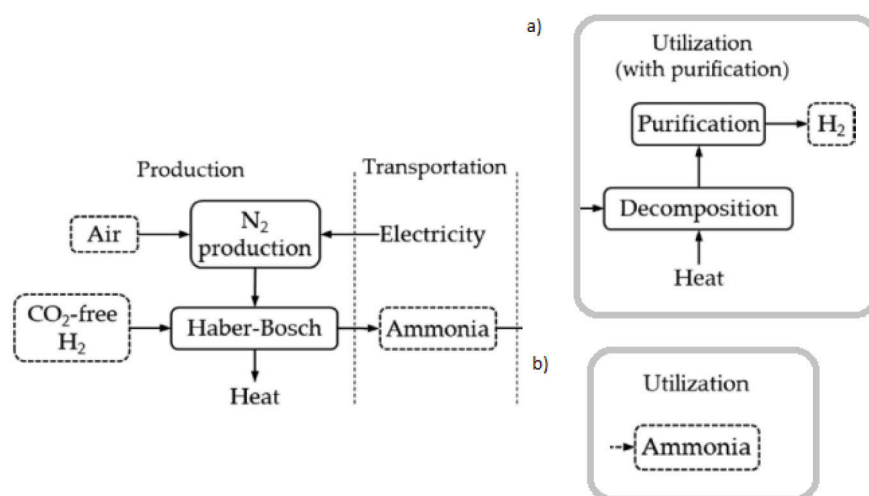


Figure 29. H₂ storage/transportation through NH₃ synthesis. A) Non-direct utilization B) direct utilization. (Wijayanta et al., 2019)

Transportation of hydrogen via pipeline

The second main alternative for transporting the large volumes of hydrogen is the gas pipeline system. The compressed gas hydrogen is usually around 30-300 bars in the pipelines. Such systems are implemented only after there has been established production and demand centers. It requires large-scale centralised hydrogen production with output of thousands ton of H₂ per year. However, pipeline networks require significant initial investment, compared to the other transportation methods, and therefore, the hydrogen market has to be mature. Another option, which requires less capital expenses is to adapt compressed natural gas pipelines for hydrogen. These network systems cannot physically be suitable for pure hydrogen transportation, but mixed hydrogen with natural gas could become a solution for the early stages of the hydrogen economy establishment.

Transportation of hydrogen together with natural gas.

Hydrogen mixed with natural gas provides an opportunity to deliver hydrogen to the end consumer avoiding the investment cost for the separate hydrogen network infrastructure. Due to the lighter molecular weight, hydrogen can be blended into the natural gas pipeline system up to a certain threshold. According to international safety regulation for handling hydrogen gas, different components of the compressed natural gas (CNG) systems show the different

operational performance and the risk of hydrogen leakage. For example, the highest hydrogen intolerance appears according to Figure 30 by the gas turbines, compressor stations, pressure valves and other metal components, indicating the possible percentage of hydrogen content from 0 to 10%. Many countries have established a maximum allowed amount of hydrogen that can be blended in the natural gas network, for example in Germany it varies from 2-10%, depending on the presence of a CNG filling station or not, 6% in France, 0,1% in the UK and 10-15% in the USA. (Gondal, 2019; Hydrogen Europe, 2019) Nevertheless, handling mixture of hydrogen and natural gas is not a new experience, as in the 20th century countries such as Germany, England and the USA in the large cities, the town gas used in every household was hydrogen rich and held more than 50% of volumetric hydrogen content. Later the network system was changed to be more suitable for natural gas. (Hydrogen Europe, 2019) Therefore, the experience of the operation of hydrogen network allows for speedy implementation of the new hydrogen resistant materials and decarbonisation of the gas system.

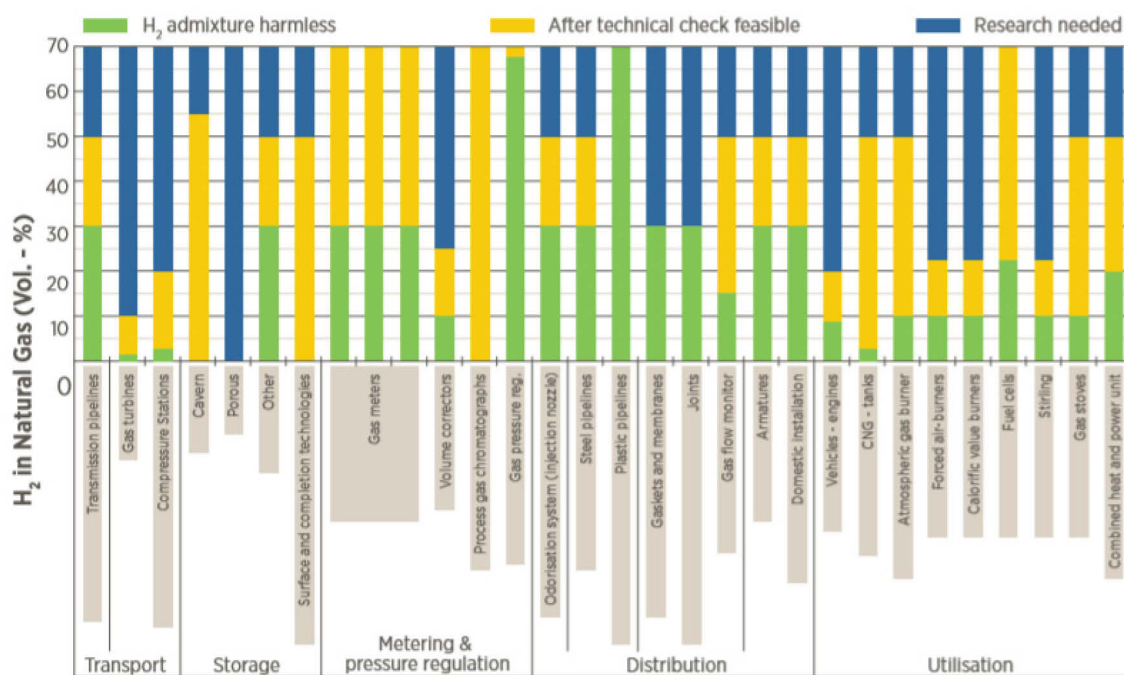


Figure 30. Hydrogen tolerance of the components of the gas infrastructure. (IRENA, 2018)

One of the downsides of blended hydrogen is its high corrosive effect on the steel components of the network systems, therefore, causing increases in permeability of H₂ and steel embrittlement. This results in the surface cracks and dangerous leakage of hydrogen. Moreover, hydrogen causes further permeability in the steel under pressure, which also impairs the stress resistance of the material. It is suggested to use low-permeable materials for steel covering, to

use carbides in order to reduce carbon content in the steel. (Gondal, 2019) Another problem associated with the hydrogen and natural gas mix is the reduction of the calorific content, which results in the different (higher) gas flow. The following is accompanied with pressure drops within the pipeline which affect the transmission and distribution gas systems. In order to avoid system errors, the research of the hydraulic properties of the combined gases is needed. (Gondal, 2019) However, modern materials for pipeline can provide better tolerance and increase the allowable amount of hydrogen. According to a study of Gazprom and VNG, the new pipeline systems Nord Stream 1 and 2, as well as Turkish Stream are capable of carrying up to 70% of hydrogen content. (Gazprom Export, 2018)

In Germany, the national gas carrier Ontras is conducting studies under the HYPOS project H2 PIMS and H2 HOME on the tolerance of blended hydrogen in natural gas systems to the household appliances. The goal is to form a development strategy for converting each household into hydrogen friendly system. (HYPOS, 2020)

Hydrogen pipelines

Globally the infrastructure of pure hydrogen is being practiced at the industrial scale and usually does not exceed 100-150 km. In total the distance of hydrogen pipelines reaches 4500 km mainly owned and operated by hydrogen producers. The USA has the biggest hydrogen network (2600 km), followed by Belgium (600 km) and Germany (300 km). (Hydrogen Europe, 2019) A pure hydrogen pipeline network requires more energy for its operation (for example for energizing the pumps) than a natural gas network. Due to the low volumetric density of hydrogen, the flow velocity has to be three times more than that of the natural gas. On Figure 31 the comparison of two gases is presented, where the energy for transporting hydrogen is increasing drastically with the distance and represents one third of the total energy carried in the form of hydrogen. Hydrogen loses a significant amount of energy due to the high increase in the flow resistance in the pipe. (Bossel & Eliasson, 2002a) Despite the lower viscosity of hydrogen, that improve the final efficiency, the energy consumption (the pumps are feed from the same pipeline) still is one of the main problems of pipeline transportation, as a higher production rate of hydrogen is required.

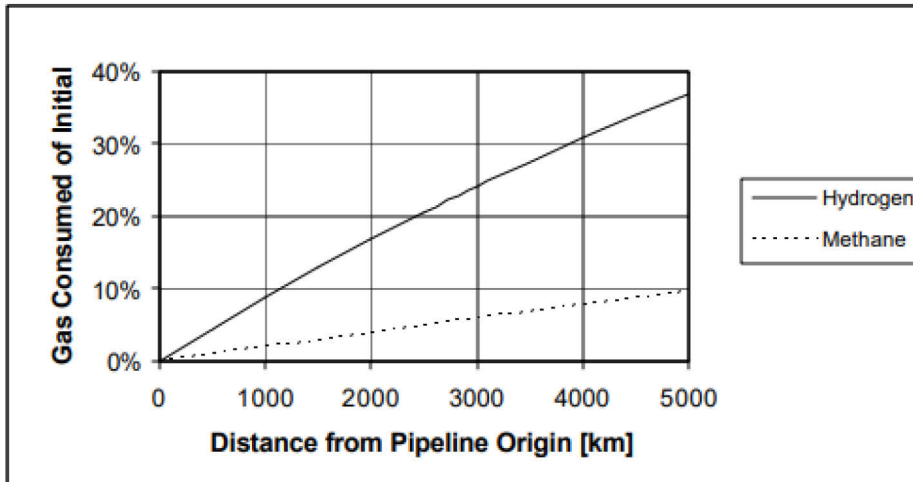


Figure 31. The fraction of the gas consumed to energize the pumps (ratio of energy needed to HHV energy content) of the transported gases. (Bossel & Eliasson, 2002a)

The material requirements for a hydrogen pipeline infrastructure have to be conformed to the International Organisation for Standardisation (ISO) standards on transporting hydrogen in liquid and gaseous form. Due to its lower molecule size, hydrogen penetrates into different alloys and causes degradation of the covering material, or so-called hydrogen embrittlement of steel materials. High temperatures can be problematic and contribute to the influence of hydrogen elements in carbon and low-alloy steels. Only limited groups of steel alloys are immune to hydrogen embrittlement under different temperature/pressure levels. They are listed in the documentation of the standard. Low melting point materials (aluminum, copper, brass and bronze) are not recommended, as they show instability at higher temperatures. Plastic pipelines can be used only under constant control in small laboratory installations, where the flow of hydrogen and pressure is low. (Asia Industrial Gases Association, 2012)

Existing hydrogen pipelines attracts a lot of attention from different interested parties in the hydrogen economy. As was mentioned earlier such pipelines belongs to the industrial site which main purpose is to supply hydrogen as a feedstock to the industries. One of such pipelines in Central Germany was integrated into the research project GreenHydroChem as Reallabore or living laboratories, under HYPOS's supervision. The purpose of such Reallabor is to test the hydrogen application in the large scale conditions. In the case of GreenHydroChem, the target is to decarbonise industry and provide electrochemical storage for the renewable energy generation. HYPOS eV, registered association in the Central Germany founded in 2013, represents a network of partners from a broad pool of competencies from business and science, in which regional potentials, expertise and experience meet. HYPOS coordinates industrial

companies from the fields of energy, chemistry or plant engineering (including Linde, VNG, Air Liquide), together with small and medium-sized companies and universities as well as research institutions. The project GreenHydroChem includes the linkage of large electrolysis (production) 50-100 MW, hydrogen pipeline (transport), hydrogen cavern (storage) and the corresponding large customers (economical use) for green hydrogen. HYPOS is aiming not only to test the green hydrogen application in a real scale, but also to transform a lignite region into a green hydrogen valley, where social benefits and values work together with innovation in order to achieve deep CO₂ reduction (estimations of 91% of CO₂ drop in the region). (HYPOS, 2019)

Transportation in the Baltic Sea.

The Baltic Sea is one of the busiest maritime transportation region and within the last year it's the harbor and ships infrastructure undergoes many changes. According to the International Maritime Organization (IMO), the International Convention for the Prevention of the Pollution from Ships, also known as MARPOL, the emissions from the maritime transportation should be reduces drastically. This means that oil transportation tankers, heavy maritime polluters (SO_x emissions), are proposed to be changed with the more environmental friendly option - LNG fuel. MARPOL has been incorporated into the European Directive 2012/33/EU (EU 2012), the upcoming adaptations caused stress on the shipping sector and challenges to its stakeholders by losing economic efficiencies and increased fuel prices. (Albrecht, 2015) All the countries that are having access to the Baltic Sea are changing their maritime shipment strategies and initiating LNG projects intensively. On Figure 32, are visible two planned LNG terminals in the Russian part: Ust-Luga, Vyborg-Vysotsk and Kaliningrad. LNG terminal Ust-Luga is planned to be commissioned in 2023-2024 with an annual production of 13 mln ton of LNG. LNG terminals in Kaliningrad was commissioned in 2019. (Gazprom, 2020b) The detailed map of the LNG terminals can be found in Appendix 6.

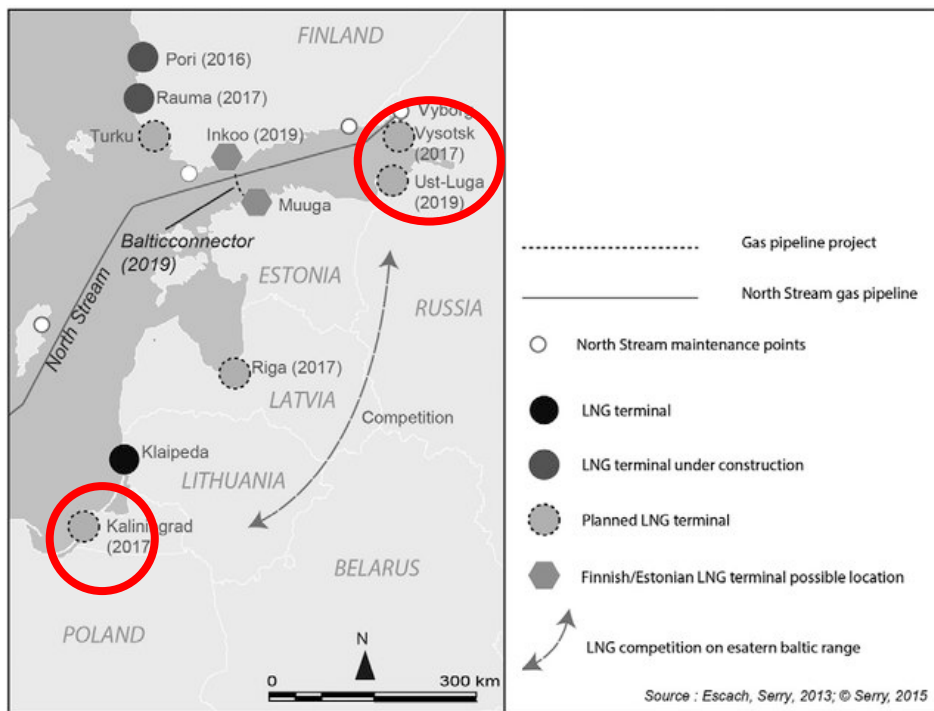


Figure 32. Map of the North-eastern part of the Baltic Sea. Overview of the planned and operating LNG terminals. (Gritsenko & Serry, 2015)

Germany is also active in the development of the liquefied natural gas industry and harbour infrastructure. LNG terminals at ports are favoured, more flexible bunkering vessels with a capacity of 6,000 to 7,000 m³ of LNG is now under focus of the investments. The LNG terminals vary in size, from large industrial scale, such as Brunsbüttel Ports (8 bcm), und Rostock Port (300.000 ton of LNG from Russia), to smaller harbours, for example in Bremen. (HELCOM, 2019)

The development of mature LNG market in the Baltic Sea can become an easy integration option for the hydrogen transportation in liquid form.

3.6 Hydrogen storage potential in Russia

Hydrogen storage facilities are a necessity in the supply chain. Since the demand on hydrogen can vary, adequate storage solutions are designed to maximum optimize the system and bring costs down. Hydrogen storage is usually classified to two groups: physical hydrogen storage and materials based storage technologies. Physical storage of hydrogen refers to the storage of hydrogen in its different states: gaseous, liquid, slush H₂ (melting point of hydrogen) and different compressed variations. In gaseous or compressed form of hydrogen the pressure varies from 10 bar up to 1000 bar. In the case of high-pressure only special solid steel or steel composite pressure vessels are suitable. Compressed hydrogen is common in mobile application. Liquid hydrogen storage has high energy density and benefits with the small size of

the tank. However the costs of handling hydrogen at $-253\text{ }^{\circ}\text{C}$ are high and are limiting the scale of utilization. The largest liquid hydrogen (LH_2) tank was presented by NASA at the Cape Canaveral rocket launch site with a volume of $3,800\text{ m}^3$. (Shell, 2017) Material based storage is commonly known for three types of storage: hydrates, liquid hydrogen carriers (LOCH MCH and NH_3 , discussed earlier in subchapter 3.4) and surface storage (adsorption of hydrogen). Hydrides and surface adsorption of hydrogen are novel methods of accumulating hydrogen, thus exist on the pilot plant scale with significantly higher costs compared to other still expensive storage methods. (Shell, 2017)

The design of the storage system in most cases depends on the end user, or better to say on the preferable pressure level of hydrogen. Figure 33 summarises the most common physical and material based hydrogen storage in terms of its fuel content density per volume (liters). The more energy dense hydrogen system storage, the more costs it carries. For example, storage of gaseous hydrogen at a low pressure of 30 bars represents about 4-5% of the energy content stored, whereas 350 or 700 bar correspond to 9-12%, and liquid hydrogen requires around one third of the total energy content. (Shell, 2017)

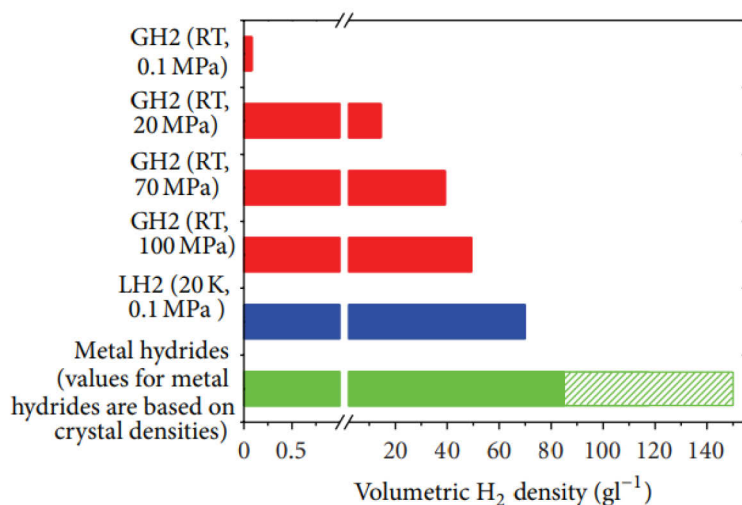


Figure 33. Comparison of volumetric fuel densities for different hydrogen storage technologies: compressed hydrogen (GH2) at room temperature for 0.1, 20, 70, and 100 MPa [36]; liquid hydrogen (LH2); and metal hydrides. (Kunowsky et al., 2013)

For the large industrial hydrogen storage, underground hydrogen storage is the most preferable option. It can accumulate vast quantities of compressed hydrogen from 10000 m^3 up to 3000000 m^3 , in order to regulate varying daily, weekly, monthly and seasonal demand. Hydrogen can be stored under different geological formations:

- depleted oil or gas fields;
- the traps of reservoir water systems (storage of natural gases and hydrocarbon liquids);
- underground tanks in salt deposits;
- deposits of permafrost.

(Basniev et al., 2010)

Naturally, these methods can be effectively applied if the corresponding facilities are constructed near large hydrogen consumers. However, the same natural gas storage systems are not suitable for hydrogen. Hydrogen is more mobile gas than methane, because of its lower viscosity and density. Thus, the storage system has to be redesigned to exclude the possibility of the gas leakage through the different seals and vessels. (Basniev et al., 2010)

In Russia underground gas storage (UGS) has more than 60 years of experience. Currently 23 UGS facilities in 27 geological structures are owned and operated by Gazprom, which in 2019-2020 equals to 72.232 bcm of natural gas. (Gazprom, 2020a) Gazprom is working towards the decarbonisation of its natural gas and hydrogen becomes one of the main long-term orienteers. As part of the hydrogen economy, research on the use of traditional underground gas storage facilities for hydrogen storage is under process. (Gazprom Magazine, 2019; Gazprom VNIIGAZ, 2018) Yakshunovskoe UGS is currently tested on the hydrogen tolerance. (Basniev et al., 2010)

The North-western region of Russia is not rich regarding URG facilities, compared to other regions in Russia. The biggest in the region is Gatchinskoye UGS located in the suburbs of Saint-Petersburg. The volume of the operating facility is approximately 200 mln m³, with maximum daily withdrawal of 2 mln m³ of natural gas. The pressure in the reservoir is estimated between 2,7 and 4,6 MPa. During geological investigations in 1960 a cave was discovered (illustrated in Figure 34), which had a crystalline basement surface and superincumbent Lower Cambrian sedimentary rocks, which formed underground voids with dome shaped folds that extend from southwest to northeast. (Gazprom, 2014) This gives a hope for further investigation of the region, especially on poorly inhabited north.

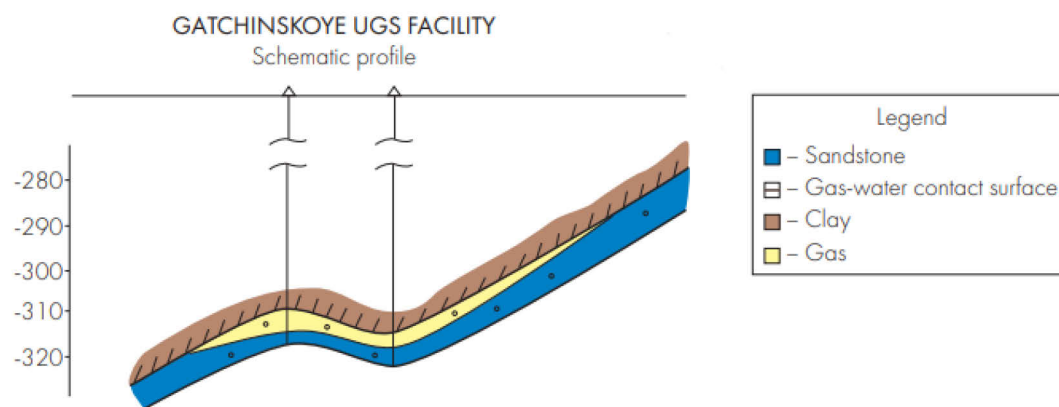


Figure 34. Scheme of underground structure of the Gatschinskoye UGS facility. (Gazprom, 2014)

3.7 Expected cost structures and efficiencies of different hydrogen generation schemes in Russia

Overview of the scenarios

This subchapter is dedicated to the analysis of the levelised cost of hydrogen (LCOH) system, designed for export from North-western region of Russia to Northern Germany via maritime shipment (liquid hydrogen, NH₃ and LOCH MCH). Figure 35 represents the conceptual supply chain for the early stages of the hydrogen export market between Russia and Germany. The numbers on the scheme stand for the different steps in hydrogen supply chain: source of electricity, electrolysis unit, compression/liquefaction of hydrogen. These four steps all together compose the hypothesis framework, on which the cost assumptions are based.

1. Source of electricity. Three energy sources (nuclear, hydro and wind) are compared for the hydrogen production. Nuclear and hydro power plants have existing capacities, therefore capital expenditure is not included into calculation, only additional operational costs. Different electricity prices are taken for the calculation of LCOH – wholesale price of electricity (normal conditions) and direct purchase of electricity from the generating facilities (exclusive tariffs for electrolysis). For wind parks three LCOH were calculated, first two according to the electricity price tariffs for the large and small industrial consumers (4 ruble/KWh and 7 ruble/kWh) and the third option represents direct supply of electricity via combining costs of the wind park and hydrogen generation facility (electricity costs are considered zero).

2. Electrolysis unit. Three electrolyser types are considered: alkaline electrolyser, polymer electrolyte membrane (PEM) electrolyser and high temperature solid oxide (SOE) electrolyzer. The costs of an electrolyser comprise capital expenditure, operational costs for maintenance

and electricity costs (for production of 1 kg H₂ 55 kWh is considered, efficiency of electrolyser 67%).

3.a + 4. Storage of Hydrogen in a tank or underground, further transportation via pipeline/ trucks to the liquefaction unit. This option is considered when the electrolyser is located off-site to the harbor zone, nearby the power generated source, as an example. Therefore, the H₂ storage tank or geological formation for H₂ storage (salt or gas fields) are designed for accumulating hydrogen near the production site, then hydrogen is sent via pipeline or truck to the harbor zone. Dependent on the size of the electrolyser, the transportation type can be chosen. Pipelines are designed for higher volumes of hydrogen, when trucks can be used for smaller size pilot-projects. Liquefaction unit is highly energy consuming, as hydrogen in liquid stage have to be kept under -253 °C. In order to optimize the total costs, hydrogen should be liquefied just before loading to the freight ship. That is why the size of the liquid storage hydrogen is minimized.

3.b Direct liquefaction of hydrogen. Another option is designed for on-site harbor production of hydrogen. Thus, the chain includes only, direct liquefaction of H₂ and liquid storage of hydrogen.

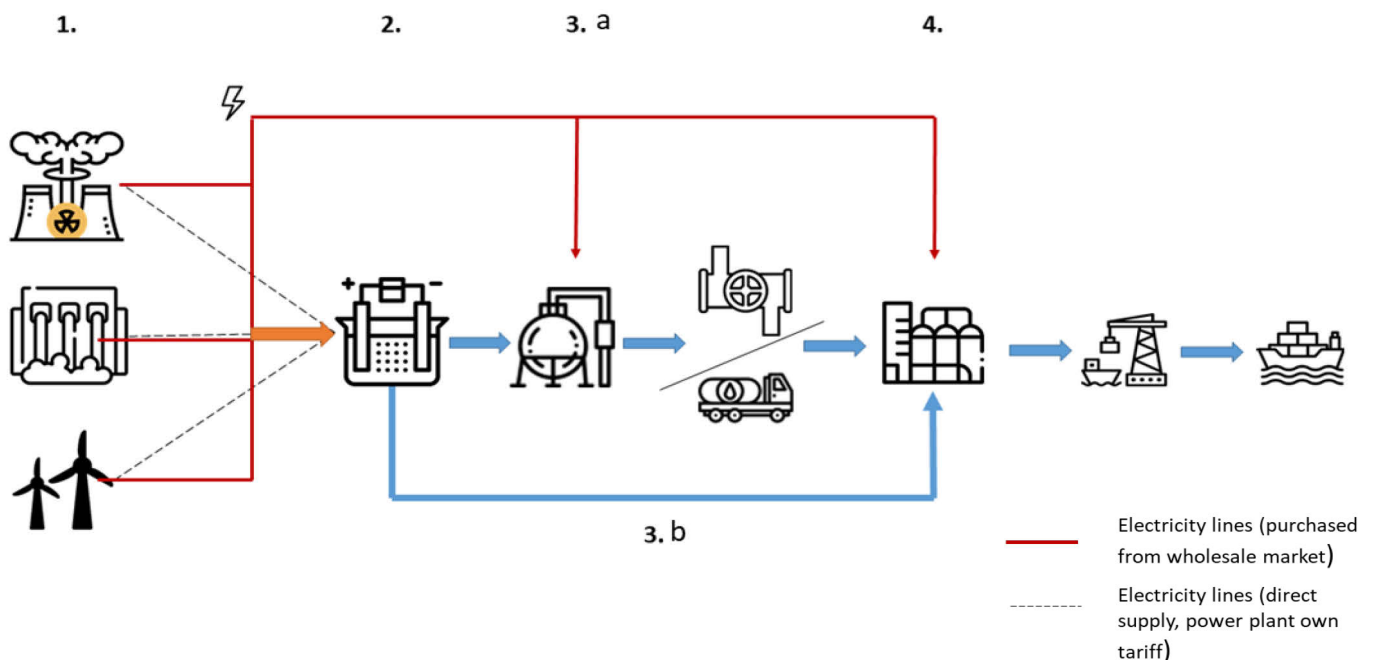


Figure 35. Supply chain of carbon-free hydrogen from production to the end transportation. Author's assumptions and design.

Therefore, based on the assumption and scheme (Figure 38) above, for each energy scenario three cases will be considered:

1. *Off-site hydrogen production with compressed tank storage*: Production of hydrogen outside the harbour zone, storage of hydrogen gas in the compressed tanks and transportation to the liquefaction facility located at the harbour.
2. *Off-site hydrogen production with underground storage*: Production of hydrogen outside the harbour zone, storage of hydrogen gas in underground caverns and transportation to liquefaction the facility located at the harbour.
3. *On-site hydrogen production*: Production of hydrogen within the harbour infrastructure and direct liquefaction for shipment.

Limitations

The LCOH does not include the construction and operation costs of new electricity grid infrastructure, the logistic costs between the production and liquefaction units (3.a case), the water consumption costs, the handling and shipment costs. The logistic costs are difficult to assess, depending on the location of the production unit, harbor, trucks capacities and etc., thus they were neglected, in order to exclude the uncertain cost parameters. Water consumption costs represent only a small part of the LCOH, therefore can be neglected in this work, especially regarding good water availability in the region. Regarding the shipment costs and harbor service costs, the uncertainty remains high, and for such a long-term prognosis could be significantly distorted.

Input data

The input data for calculation of the LCOH was taken from the database of project ASSET “Technology pathways in decarbonisation scenarios” funded by the European Commission in 2018. In the report the costs are classified according to the year of investment. Due to the low commercial level of the hydrogen related technologies, the most optimistic scenario was taken, the costs values refer to the class “2050” and “Ultimate”). Table 14 provides the list of abbreviations for different hydrogen related technologies used in this work, values of which were taken from ASSET for calculation LCOH. The complete input cost parameters and values can be found in Appendix 3. (Capros et al., 2018).

Table 14. Abbreviations of the compartments of the designed hydrogen system.

Symbols:	
alk	Alkaline electrolyser
PEM	PEM electrolyser
SOE	SOE electrolyser
t	tank storage
u	underground storage
CAP	Capital expenditure
O&M	Operation and maintenance
ELCO	electricity cost

Assumptions

The levelised cost of hydrogen was calculated based on the approach presented in Nicita et al. (Equation 1) (Nicita et al., 2020). The degradation rate and tax rate were excluded from the equation. The size of the annual production represents one 100 MW electrolyser unit with an average daily production rate of 50000 kg of H₂. The availability factor varies depending on the energy source: for nuclear power plant it was assumed 85%, for hydro power plant 80% and for wind parks 40%. The electricity price is assumed 1 ruble/kWh and 4 ruble/kWh (0,011 €/kWh and 0,044 €/kWh respectively), which reflect the situation on the wholesale market of Russia for large electricity generation objects (nuclear and hydro). For wind parks the values for electricity prices are 4 ruble/kWh (0,044 €/kWh) and 7 ruble/kWh (0,077 €/kWh). Table 15 comprises the main assumptions to the technical parameters of each unit of hydrogen supply chain.

Table 15. Main technical assumptions of supply chain components considering the size of the hydrogen production

System unit	Description
Electrolyser	Alkaline electrolyser, 100 MW, efficiency
Compression unit	100 MW, Up to 10 bar/200 bar
Storage of compressed H ₂ (CH ₂)	Pressurized tank: 22.000 m ³ ; 7day storage ~11.655 MWh Underground storage: 1.500.000 m ³ ~11.655 MWh
Liquefaction unit	100 MW
LH ₂ Storage	1.250 m ³ , 2 days storage, ~ 3.330 MWh
Life time of the project	25 years

Equation (1) represent the calculation of LCOH.

$$LCOH = \frac{\text{Total lifetime cost}}{\text{Total lifetime hydrogen production}} = \frac{CAPEX + \sum_{n=1}^N \frac{OPEX}{(1+r)^n}}{\sum_{n=1}^N \frac{Mn}{(1+r)^n}} \quad (1)$$

Where,

r - interest rate in Russia (10-12%) ;

Mn – annual production of hydrogen in kg;

n – amount of years, 25 in the scenarios

Equations (2) and (3) reveals the concept of capital and operational expenditure respectively.

$$CAPEX \left(\frac{\text{€}}{\text{kW}} \right) = (CAPEX_{\text{powerplant}} + CAPEX_{\text{electrolyser}} + CAPEX_{\text{liquefaction}} + CAPEX_{\text{storage}}) \times \text{Capacity of electrolyser} \times 100 \quad (2)$$

$$OPEX \text{ for year } n \left(\frac{\text{€}}{\text{kWh}} \right) = (OPEX_{\text{powerplant}} + OPEX_{\text{electrolyser}} + OPEX_{\text{liquefaction}} + OPEX_{\text{storage}}) \times \text{Capacity of electrolyser} \times 1000 \quad (3)$$

Transportation costs

The calculation of transportation costs is not included in LCOH, in order to avoid confusion between the compartments of the supply chain and for easier comparison, since many studies include only first stage of hydrogen supply chain, Figure 36.

The basis of estimating the marine transportation costs lies on the assumptions of Wijayanta et al. of the hydrogen shipment from Australia to Japan, a distance which is approximately 9000 km. In the case of transporting the hydrogen from the North-western region of Russia to the northern LNG harbours of Germany in the Baltic Sea, the distance is 1.500 km. (Wijayanta et al., 2019) In order to scale down the maritime shipment costs (which is mainly based on the fuel consumed during the journey), 0,02 €/kg of hydrogen transported per 1.000 km was assumed. The volume of hydrogen to be stored in the tanker corresponds 1.250 m³ in liquid state. Figure 39 shows the resulted costs associated with transport from hydrogen in different liquid states. All of the liquid methods show approximately the same cost at 1,4-1,5 €/kg of hydrogen transported. In case of ammonia transportation, the cost can be reduced to 1 €/kg if the end product is ammonia and do not require dehydrogenation step.

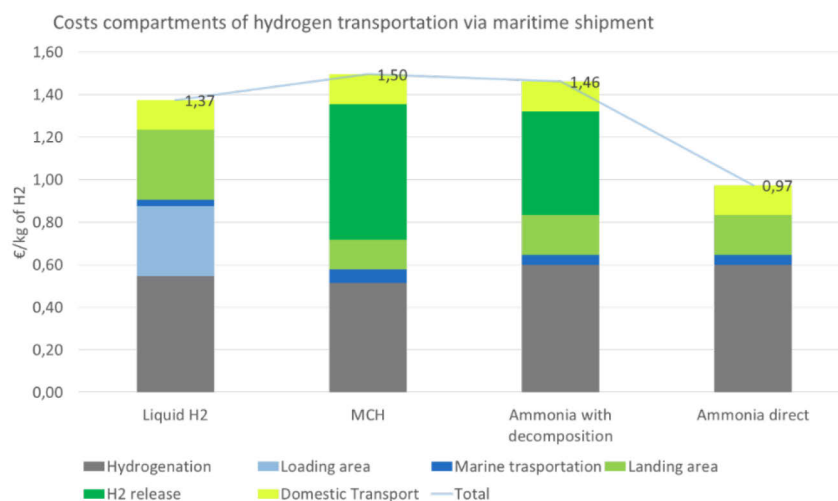


Figure 36. Comparison of the maritime transportation of hydrogen in liquid forms (liquid hydrogen, MCH and ammonia). Adapted from (Wijayanta et al., 2019)

Results

The calculations were conducted in order to analyse the potential cost of hydrogen produced in Russia, its sensitivity to the different tariffs of the wholesale market and which steps of the supply chain are the most problematic. LCOH was calculated for three sources of energy: nuclear PP, hydro PP and Wind Park.

All results gathered are representing alkaline electrolyser, excluding PEM and SEO. During the calculations the alkaline and PEM electrolysers showed similar result, whereas SEO electrolyser had higher values. Alkaline and PEM electrolysers in general are expected to produce large volumes of hydrogen, and PEM electrolyser, which used to be the more expensive option, is now gaining momentum and reaching the same scale level as with its conventional competitor –alkaline electrolyser.

The first two scenarios aimed to provide an understanding on how the unutilized capacities in the region can produce carbon-free hydrogen and if it could be a viable economic option to open a window of hydrogen supply to Europe. The Russian electricity market is more regulated than, and not as flexible as, its German analogue. Electricity can be purchased on the wholesale market and not directly from the producer, which increases costs significantly. The LCOH was calculated with the wholesale market price of 4 ruble/kWh and 1 ruble/kWh, the condition if there were an exclusion in the regulated document for power-to-gas systems and the electricity cost would represent then the direct purchase from the power generation object. Figures 37 and 38, combine the LCOH from nuclear and hydro respectively and shows two tariffs for each

supply case. Moreover, the diagrams represent the role of the compartments of the hydrogen system in the total cost. The electrolyser costs were divided into three parts: capital expenditure (CAPEX), operation and maintenance (O&M) and electricity costs. The resulted LCOH show that, the cost derived from the market electricity price, would be in average 2 times greater, than the direct purchase as for nuclear, as well for hydro scenario. The reason for that is the greatest part of the LCOH stands for electricity consumption costs. In 1 ruble/kWh tariff it shares 35-40% of the total cost and in 4 ruble/kWh it shares 65-70%. The detailed results are provided in the Appendix 4.

Regarding the supply cases, the onsite production case has the lowest end cost of hydrogen 2,9 €/kg in nuclear scenario and 2,38 €/kg in hydro scenario. However, this option is calculated for limited amount of liquid hydrogen storage – 3,5 times less than for the compressed storage in other cases. Storing hydrogen in liquid state requires a lot of electricity, therefore the scale of storage was designed to just match the shipment volumes. The off-site hydrogen supply chains are designed for larger volumes of production. The underground storage cost of hydrogen is 6 times less than storing in pressurised tanks (0,05 to 0,36 €/kg). In total hydro PP provides slightly more economically incentive hydrogen than nuclear PP. on average, every case is different only by 0,5 €.

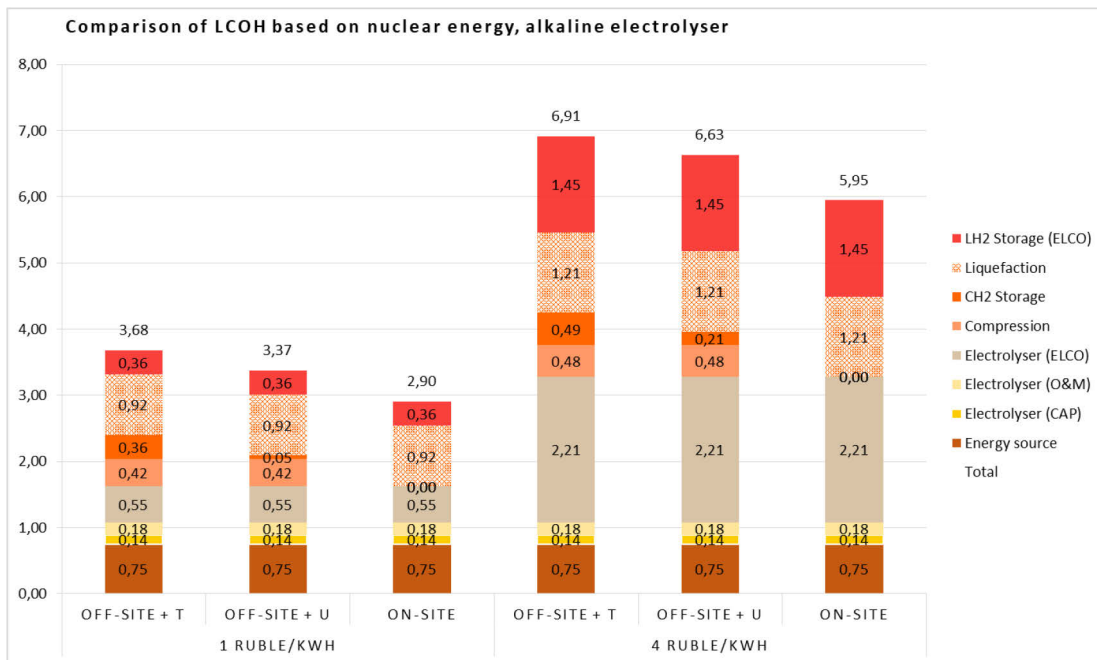


Figure 37. Nuclear based hydrogen. Comparison of LCOH (€/kg) with different electricity cost 1 ruble/kWh (0,011 €/kWh) and 4 ruble/kWh (0,011 €/kWh)

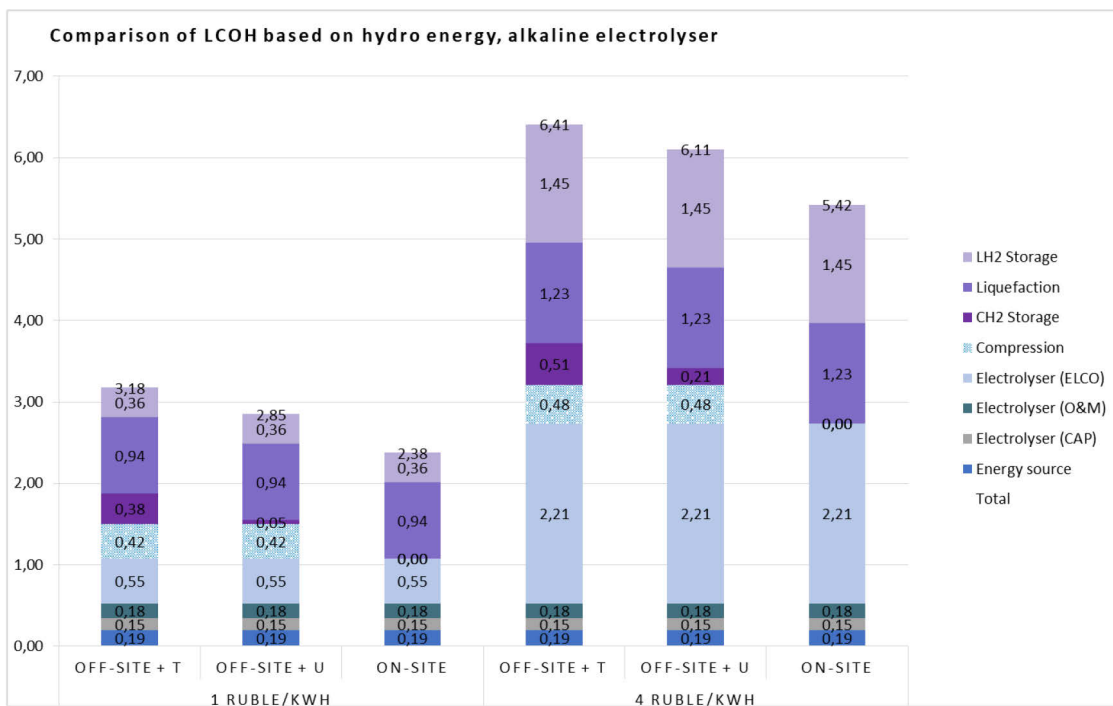


Figure 38. Hydro based hydrogen. Comparison of LCOH (€/kg) with different electricity cost 1 ruble/kWh (0,011 €/kWh) and 4 ruble/kWh (0,011 €/kWh)

Wind-based hydrogen has different assumptions in terms of electricity price than the first two alternatives. The LCOH were calculated with two different price tariffs: 4 ruble/kWh and 7 ruble/kWh, which represent the electricity prices for large and small industries on the Russian wholesale market. Currently there is no wind market, as most of the projects operate as pilot projects and cannot be compared to the large power plants. In a long-term perspective, it is

highly uncertain, whether the variable renewable energy generation will reach the same level of wholesale market penetration as it is happening in Europe now. The resulted cost of hydrogen from wind was established at the range 6,12-7,52 €/kg for the price tariff 4 rubles (0,044 €/kWh) and 150% higher for 7 rubles (0,077 €/kWh) – 9,09-10,67 €/kg (Figure 39). The electricity supply for electrolyser operation refers to the half of the LCOH, the other half mainly consists of the electricity requirements for the liquefaction. Therefore, the electricity represent 75-90% of the total cost. The assumptions for the third LCOH, which is named “LCOE wind, direct to electrolyser” in Figure 39, were based on the idea of the direct connection of the wind park to the electrolyser and avoiding the option of acquiring electricity in the wholesale market. Therefore, LCOH comprises CAPEX and OPEX of the wind park and excludes any costs for the electricity consumption. The resulted hydrogen cost varies from 6,59 to 7,73 €/kg, where more than 67% of the total costs corresponds the part of the wind park. In the case of wind-based hydrogen the direct purchase of electricity from the wind park for the hydrogen generation facility will not be feasible and competitive with other LCOH, until the CAPEX cost of wind turbines is reduced, for example by at least 30-50%.

Comparison of LCOH in (€/kg) based on wind energy, alkaline electrolyser

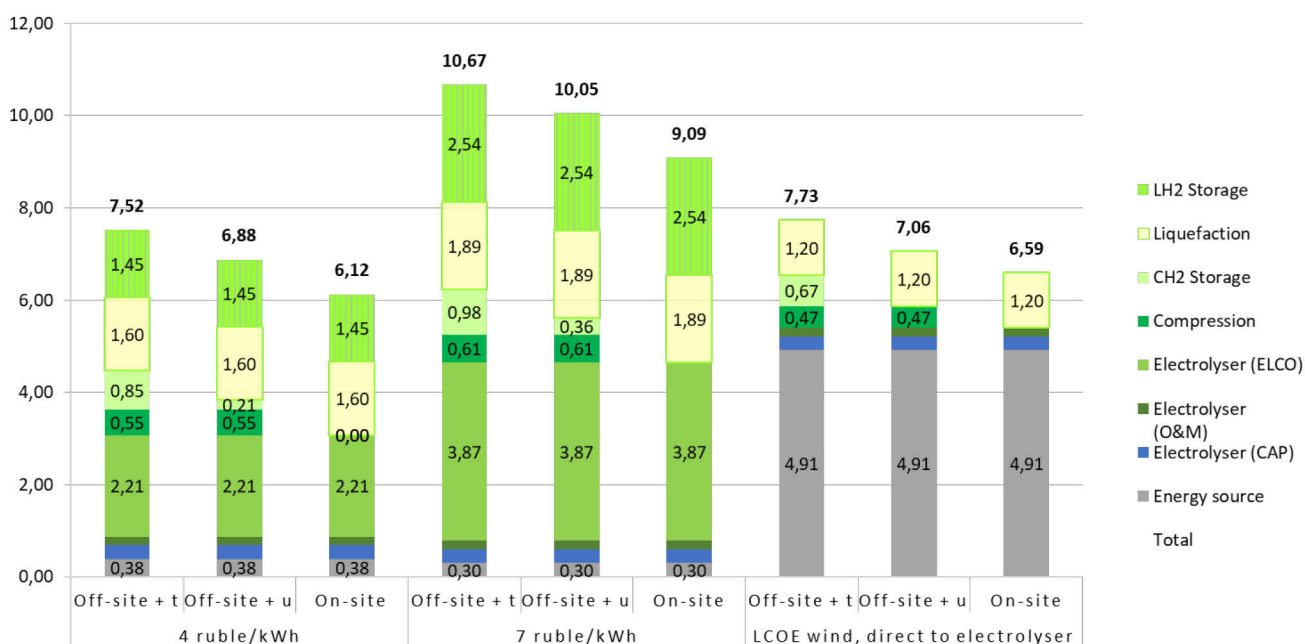
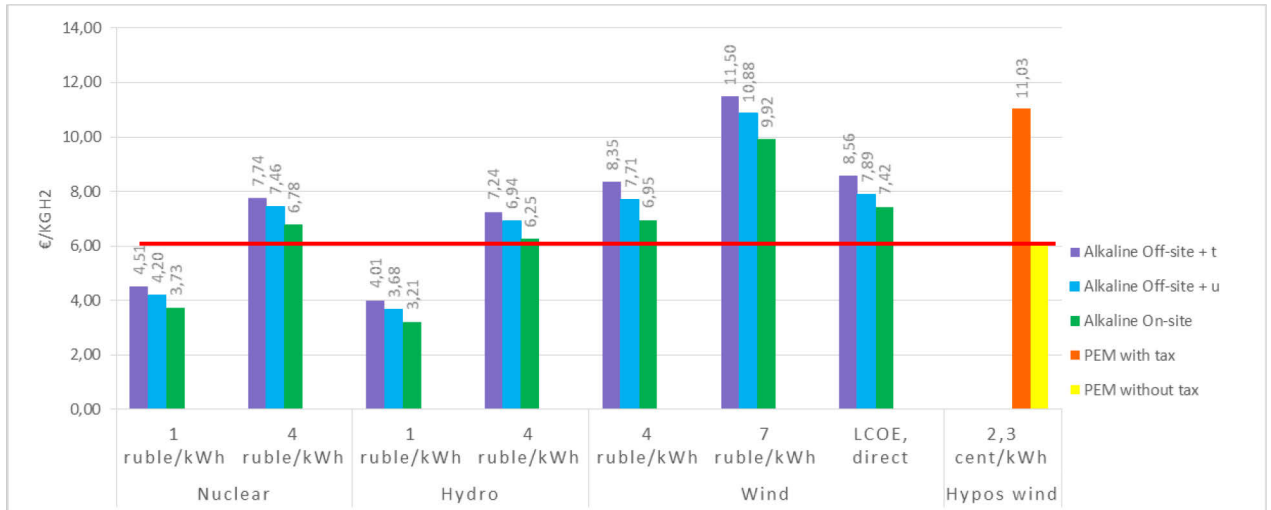


Figure 39. Wind-based hydrogen. Comparison of LCOH (€/kg) with different electricity cost 4 ruble/kWh (0,044 €/kWh) and 7 ruble/kWh (0,077 €/kWh) and direct supply of electricity to the electrolyser.

Figure 43 encompasses all the resulted LCOH (including the transportation cost of hydrogen in liquid form to Germany) with different scenarios, as well as the price for the domestic

production of hydrogen in Germany as a benchmark. HYPOS has conducted the study, where the LCOH was calculated for 100 MW PEM electrolyser with a daily production rate of 50000 kg of H₂ and operating hours of 6000 h/year. More details are available in Appendix 5. The orange bar on Figure 40 corresponds to the German cost of hydrogen (including only the production step) with the current grid taxes and regulations. The discussion on the exception of power-to-gas/x/liquid from the grid tax, so-called EEG Umlage, which corresponds to half of the LCOH, is open in the German government. Thus, the cost of hydrogen can drop from 11 to 6 €/kg. Considering this value as a H₂ price benchmark, the Russian hydrogen has good chances on the potential German market. Power-to-gas systems, supplied by nuclear and hydro power plants, can produce hydrogen at already acceptable price levels (for both of the tariffs). For Russia that can be a signal for restructuring the algorithm of the electricity purchase on the wholesale market in order to foster the development of the renewable small and medium operating capacities as well as introduction of the power-to-gas systems. Apart from opening perspectives on the new market horizon, the Russian energy system can benefit by the increased efficiency and flexibility.

i = 10%



i = 12%

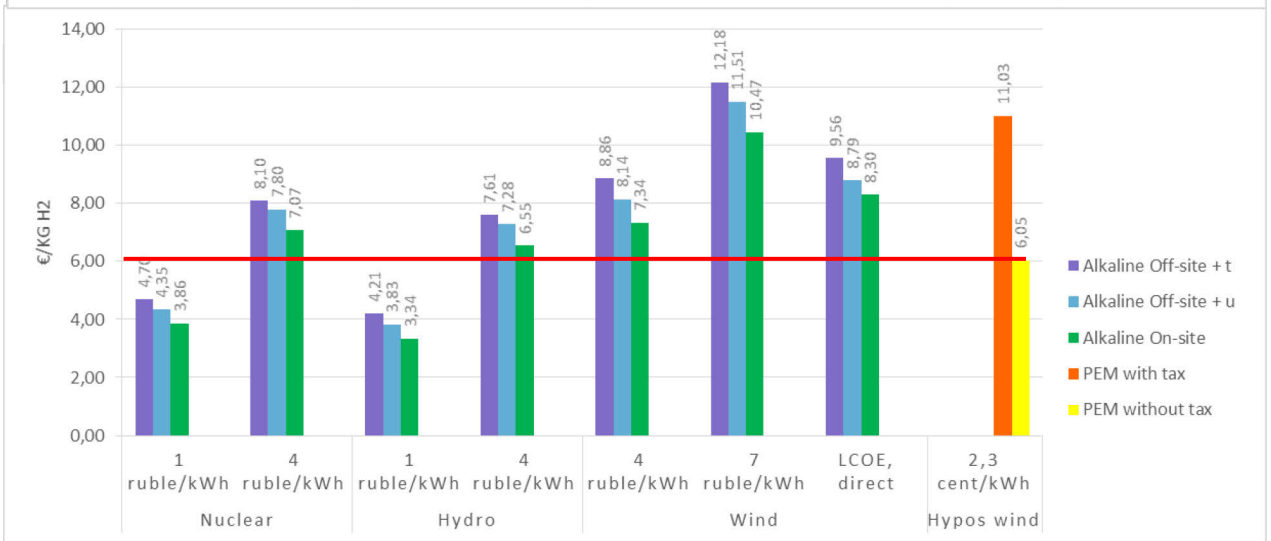


Figure 40. Summary of all results (transportation cost of hydrogen in liquid form from Russia to Germany is included), comparison between different scenarios with the different interest rate 10% and 12% and to German domestic H2 (HYPOS)

Key points of Chapter 3.

- 1) The Russian energy system is considered one of the most comprehensive and largest in the world. Thermal power plants (gas, coal and oil) have the majority of the capacity, representing 70% of the total, followed by hydro (20%), nuclear (10%) and renewable wind and solar (0,3%) capacities installed. Due to the stable energy demand in Russian energy system and slow decommissioning of the old inefficient capacities, the problem of overcapacity in the energy market occurs, which was 20 GW in the winter term and 30 GW in the summer term in 2017.
- 2) The question of decarbonisation is not on the agenda of the Russian energy strategy. Russian electricity sector is considered as one with the minimum GHG emissions in the world, due to approximately 80% of capacities installed represent by natural gas, hydro, nuclear and renewable energies.
- 3) In the latest Energy Strategy 2035 of Russia, was highlighted the importance of the low-carbon energy sources, such as intermittent renewable energy sources and energy storage. Hydrogen was mentioned in the strategy, not only as the energy storage medium, but also as potential export commodity. The target of hydrogen export in 2035 should reach 2 million tonnes per year. The potential H₂ markets are Europe and the Far East (Japan and China).
- 4) The North-Western region of Russia was chosen as the potential strategic hydrogen sector with a focus on export to German and European hydrogen markets. . The strategic geographic location of the region is one of the main benefits, as it provides a direct access to Germany via the Baltic Sea. Three energy sources were chosen for production of hydrogen – nuclear, hydro and wind. In the region the issue of the unutilised power capacities exists (nuclear and hydro). The overall production capacity of hydrogen in the North-western region can roughly be estimated at 430 thousand tons of hydrogen per annum, when utilizing the electricity generation facilities. The wind-based hydrogen is considered to be realized after 2030, when nuclear- and hydro- based hydrogen supply chains can be established after 2025.
- 5) Levelised cost of hydrogen (LCOH) were calculated for each energy source, for three different supply chains and for different electricity tariffs (0,011 €/kWh, 0,044 €/kWh and 0,077 €/kWh). All of the LCOH were compared with the H₂ benchmark cost 6 €/kg, which represents domestic production of green H₂ in Germany.
- 6) Nuclear- and hydro- based hydrogen supply chains showed already acceptable price levels (for both of the tariffs). In the best case scenario (lowest el. Price = 0,011 €/kWh, direct purchase) LCOH from hydro PP 2.4-3.1 €/kg, followed by nuclear 2.9-3.7 €/kg and wind 6.1-7.5 €/kg.
- 7) Electricity plays the main role in LCOH. For example, when industrial consumer tariff (0,044 €/kWh) increases LCOH twice fold, the electricity cost represents 60-90% of the total cost of H₂ instead of 35-40% with electricity tariff of 0,011 €/kWh.

Chapter 4. Strategic analysis and perspectives of the Russian-German-European hydrogen market

4.1 German hydrogen Roadmap 2050

For this master thesis a roadmap for hydrogen development, released in 2019 by The Fraunhofer Institute for Systems and Innovation Research ISI and The Fraunhofer Institute for Solar Energy Systems ISE, was taken as the most accurate overview of all German activities related to the green hydrogen development up to 2050. (Hebling et al., 2019) Green hydrogen will undoubtedly contribute as a decarbonisation vector, supporting wind and solar. It will also act as a replacement for gaseous and liquid fossil fuels in industry, transport and the heating sector. On Figure 41 the roadmap is presented. It is divided into the decades from 2020 up to 2050 and in the different sectors of hydrogen development, such as Research and Development (R&D), market, technology and policy. Each of the sectors plays a crucial role.

2020-2030

The first phase in the development of the hydrogen economy is a preparatory phase. The main active areas are R&D, technology and policy. Key changes and improvements in these areas need to be made, in order to lay the foundations for starting the new hydrogen market. To penetrate the energy market, an electrolysis market of GW-scale in Germany must be built by 2030. This includes, in particular, the establishment of hydrogen supply chains and a competitive electrolysis industry, to serve the national and international market. Power-to-Gas technology has to be recognised and adapted as the regulatory framework for the installation and purchase of electricity from electrolyzers, thus minimising grid taxes and levies. (Hebling et al., 2019) The main hydrogen application sectors are industries (steel, chemical and refinery) and transport. Therefore, strong R&D is dedicated to these two sectors. As an example, stark investigation of flexible industrial systems that can cope with changing feedstocks and volume flows of hydrogen, further research of methane pyrolysis and an analysis of the effects of feedstock changes on cross-industrial material flows, are some areas where research has to be done. The transport sector requires a significant further development of fuel cell vehicles and the establishment of a refuelling infrastructure, for light as well as heavy duty vehicles. It should be noted that trucks have significantly different requirements in regard to hydrogen quantities.

2030-2040-2050

According to Hebling et al., the ramping up of the hydrogen market starts in 2030 from 4-20 TWh and increases up to 250-800 TWh in 2050. The installed capacity of the required electrolyzers in order to satisfy the hydrogen demand should be already established at 1-5 GW and is expected to expand up to 50-80 GW in 2030 and 2050 respectively. The industry will have the biggest share of H₂ demand – 6 TWh in 2030 and 38-56 TWh in 2050, see Figure 41.

Hydrogen infrastructure development is another pillar of the hydrogen roadmap. Authors of the German hydrogen roadmap suggest, that the natural gas infrastructure should be gradually retrofitted for carrying hydrogen. Starting at the beginning of the 2030s hydrogen is mixed with natural gas and by 2050 the pure hydrogen network should be already operational. (Hebling et al., 2019) The less hydrogen intense but, nevertheless, important sectors are power generation and heating. The power generation sector mainly represents R&D on electricity generation via gas turbines operated with hydrogen and fuel cells. Contribution of hydrogen to security of supply is realised via providing extensive long-term energy storage for balancing of the renewable energy generation.

The hydrogen roadmap presented on Figure 41, mentions the establishment of international trading systems of hydrogen and hydrogen based synthetic fuels. An important part is the formation of the international logistic routes of carbon free hydrogen. The roadmap covers logistical questions, such as R&D of hydrogen shipment in liquid state, ammonia, LOHC and as an alternative to the pipeline network. The entire supply chain from the technological point of view already exists on pilot project scale. Further massive investments in hydrogen systems will help to reduce the expenses and ramp up the market. International research cooperation and energy partnerships are an essential prerequisite for long-term trade relationships.

Germany hydrogen Roadmap 2050

Source: Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe

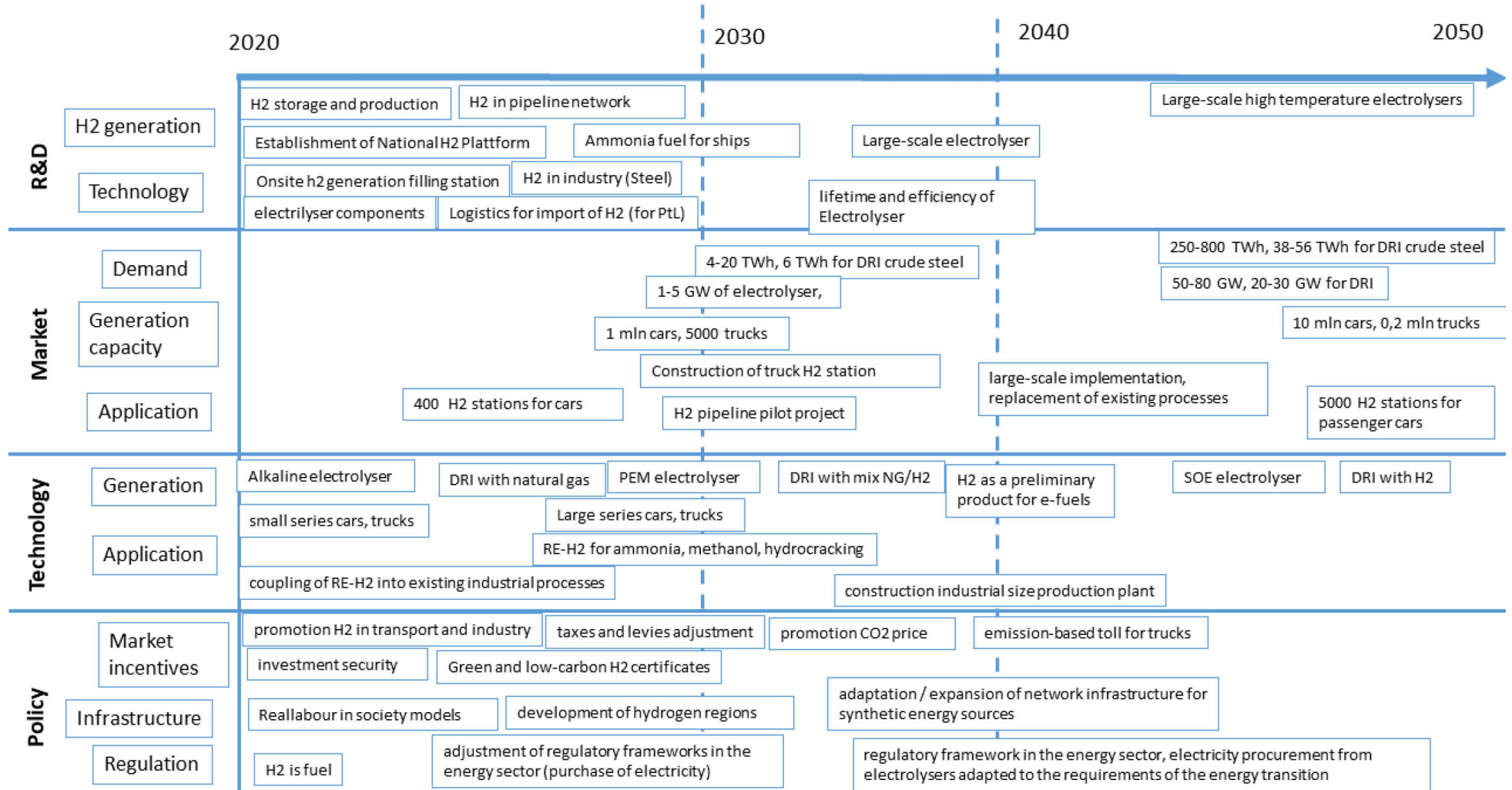


Figure 41. German hydrogen roadmap 2050. Adapted from (Hebling et al., 2019)

4.2 Russian hydrogen Roadmap 2050 oriented to the German (the EU) hydrogen market

International activities on the hydrogen development should not be ignored by Russia, as potential areas for economic and technological cooperation. Russian interest on hydrogen can be divided geographically into two regions: the Far East region with potential hydrogen market in Japan and the North-Western Region with a target on the EU, starting from Germany. The German ambitious plan of integrating hydrogen and e-fuels in the energy system opens up a fundamental opportunity for Russia to offer new pilot projects, which will provide a window to make an application for a significant share in the emerging German and European hydrogen markets.

Important competitive advantages of Russia are the availability of production capacity reserves, geographical proximity to potential sales markets, as well as the presence of an existing transportation infrastructure (established harbours and LNG export routes, which could be used for hydrogen as well). Along with the export sector, the use of hydrogen energy has great prospects within the country, allowing to reduce emissions of pollutants to the atmosphere and ensure energy supply to a significant proportion of consumers of isolated territories. In order to effectively use the potential of hydrogen energy available in Russia, the Ministry of Energy of Russia proactively initiated the development of a hydrogen roadmap of the Russian Federation, which should create the prerequisites for ensuring the scientific and technological leadership of the country in this area. The release of the official hydrogen roadmap is scheduled on the second half of the 2020.

In this chapter the hydrogen Roadmap for a Russian-European cooperation was created with a focus on the supply of large volumes of hydrogen to Germany on the first place. The Russian roadmap reflects the personal assumptions of the author of this master thesis, see Figure 42.

2020-2030

The official start of the discussion and prognosis on the hydrogen development was driven by including H₂ in the latest Energy Strategy 2035 by the Ministry of Energy of the Russian Federation. In the end of 2019 the Minister of Energy of Russia, Alexander Novak created a hydrogen working team, consisted of the main interested stakeholders: the Ministry of Foreign Affairs, Ministry of Eastern Development, Ministry of Education and Science, Gazprom,

Rosatom, as well as the scientific and expert community. The hydrogen working team was established for the assessment of the potential of hydrogen technologies and for building a roadmap for the initiation of a H₂ society in Russia on the same level with international hydrogen leaders. (Ministry of Energy of the Russian Federation, 2020a)

Figure 42 represents a Russian hydrogen roadmap oriented on the German (European) energy market. In Russia hydrogen plays an entirely different role than in Germany. The main target for Russia's hydrogen working team will be to form a hydrogen technological complex, with an export supply chain and a unique design infrastructure, which will allow the initiation of trade between Russia and Germany in 2030, where the hydrogen market is expected to expand significantly. The first step is similar to the one in the German Roadmap (see Figure 41) – to enable the National H₂ platform, which covers R&D activities of each step of the supply chain (electrolyser, compression/liquefaction of H₂, storage and transportation). To accelerate the process, a cooperation with German research and industrial organizations, should be established. German engineers have already shown professional experience in the hydrogen field, as an example, via the construction of large scale electrolysers, storing hydrogen in salt caverns and in a liquid state. On Figure 42 the areas for possible international cooperation and knowledge exchange are marked with a light blue background.

In terms of the production of carbon free hydrogen, Russia has a preliminary advantage. As was discussed in Chapter 3, the North-western region of Russia has plenty of unused installed capacities of NPPs and HPPs. Two NPPs Kolskaya and Leningraskaya can provide of more than 1 GW in total for electrolysers, already before 2030. According to an estimation from the EnergyNet consulting agency, this would result in 160 thousand tons of H₂ annually, and by unlocking the non-operating capacities it could increase 2,5 times up to 430 thousand tons per year up to 2030. The total potential of hydrogen production from the surplus capacities in Russia with increased capacity factor of 85% can be estimated at 3,5 mln tons of hydrogen per year and can be realized already in 2030. Therefore, the first international pilot projects could be initiated in the next decade. R&D activities should cover specific areas such as long-distance transportation of hydrogen and sufficient harbor infrastructure (liquefaction of H₂ and storage) in case of maritime shipment. The basic two options for exporting hydrogen are cargo ships (same logics as LNG) and pipeline networks (Nord Stream 1 and 2 can carry mixed H₂ and CH₄). During 2020-2030 the infrastructure should be implemented and tested for large pilot projects.

On the policy level some changes have to be considered too. In Chapter 3 the LCOH were compared by assuming two electricity tariffs, and competitive prices for hydrogen were only enabled for the cheaper electricity tariff – 1 ruble/kWh. If large scale industrial electrolyzers existed currently, they would not be able to purchase directly the electricity from the generation unit, but only via wholesale market regulated by the Market Council. The high electricity tariff will not allow to establish hydrogen export at a competitive price, thus PtG technology should become the exclusion of such rules. Standardization of hydrogen is another example of the political changes needed to be made and especially the part of safety and technical regulations. In Russian legislation hydrogen is considered, for example, as a hazardous industrial gas. Therefore, all steps of hydrogen supply chain have to be documented and be consistent with the standards ISO.

Initiation of the hydrogen economy could become an incentive to pay attention on the renewable energy in Russia. Green hydrogen is the product of renewable electricity and in terms of environmental impact is better compared to yellow, therefore, has more acceptance among European countries. In Russia the wind and solar markets are experiencing an emerging period, and the growth of the number of installed wind turbines is hard to predict. Nevertheless, the wind potential in the North of Russia is assessed as very high, which can be realized in new wind-hydrogen projects applicable as for export, as well as for the establishment of independent island type grid systems for isolated areas.

2030-2050

In the second period of the establishment of the hydrogen economy, market activities should take place from the beginning of 2030. By this time the pilot projects have to show successful and cost efficient production, conversion and logistics of hydrogen to Germany, so it can be introduced to the real scale production. Hydrogen supply profiles of Germany will form and grow analogously to the internal German hydrogen market.

Russia could, according to approximations regarding hydrogen and e-fuels, realistically supply 10% of Germany's total hydrogen demand (as discussed in chapter 2), which is 10-80 TWh annually, or 2,5-20 GW of electrolyzers' installed capacity. The annual production of hydrogen, based on the mentioned installed capacities, would vary from 0,46-3,7 mln tons of hydrogen. One of the main challenges for the period 2030-2050 is to develop maritime transportation for the produced hydrogen. Three main candidates are liquid hydrogen, ammonia or liquid organic

hydrogen carriers. All three have their own advantages and disadvantages (see Chapter 3), and the choice of the right option would be based on the specific design of the supply chain, simulations and technical-economic assessment and the preference of the end consumer.

Russian hydrogen Roadmap 2050 oriented to the German (the EU) hydrogen market

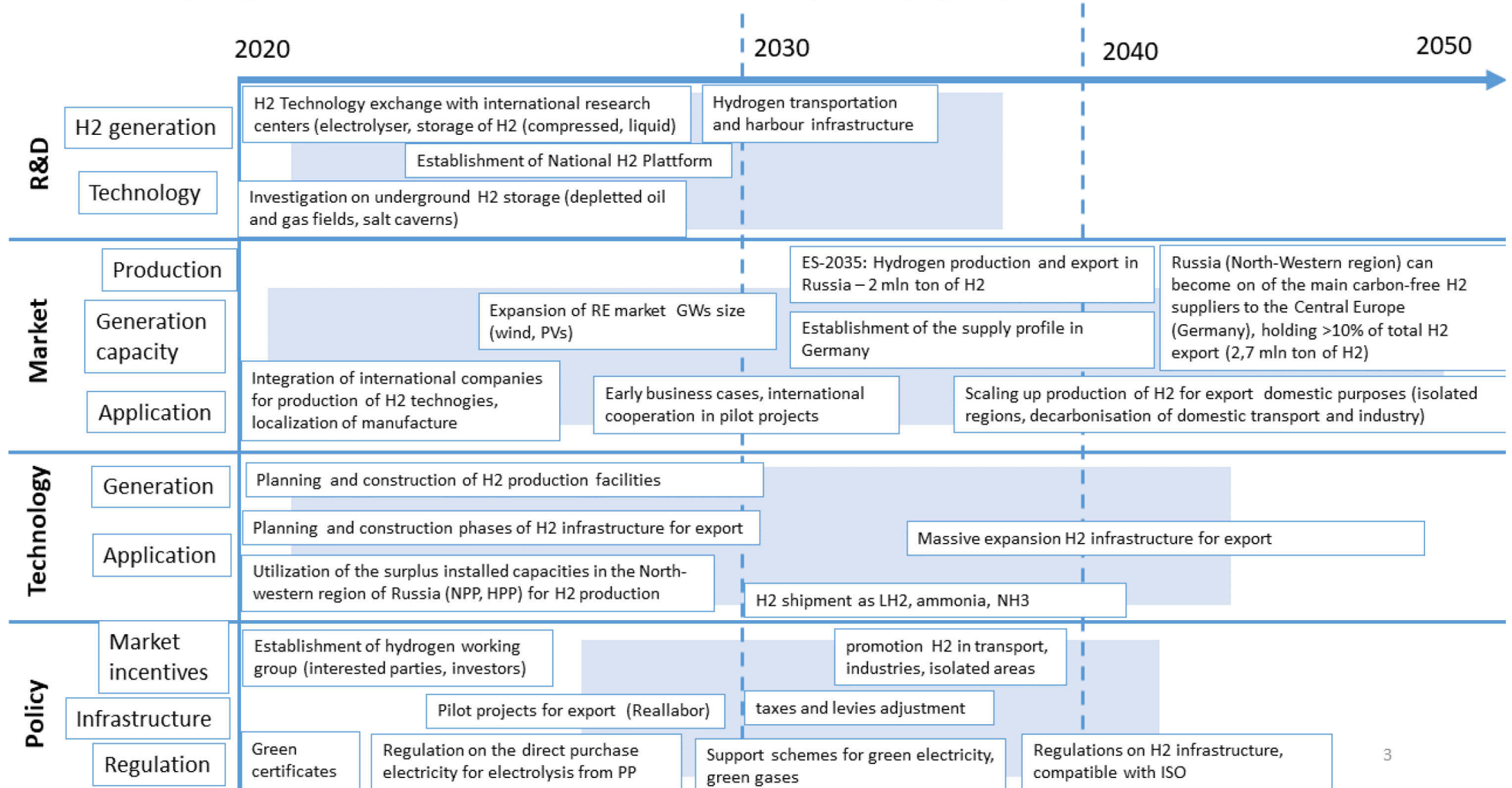


Figure 42. Russian hydrogen roadmap 2050.

4.3 Discussion on sustainability criteria for green hydrogen

Currently in Europe and around the globe there is no established green hydrogen certification system. The EU Renewable Energy Directive (RED II) has sustainability criteria developed for biomass, however, regarding the renewable gases the directive does not differentiate. Several policy studies have been released recently, one of them by Agora on the future costs and support schemes for hydrogen and synthetic fuels. (Agora Verkehrswende, 2018) The authors highlighted the main sensible zones of hydrogen, on which sustainability criteria (see Table 16) should be based:

Table 16. Overview of the sustainability criteria for green and low carbo hydrogen. Adapted from (Jensterle, Narita, Piria, Samadi, et al., 2019)

Criteria	Description
GHG emissions	Threshold of at least 70% GHG emissions reduction reached via hydrogen technology (entire production chain)
Electricity demand and additionality of renewables	The electricity from additional renewable energy capacities. (however, for H ₂ and e-fuels export is questionable)
Water usage	Region impact assessment. Sustainable water management plans
Land use	Region impact assessment. Ban in nature protection areas
Social and economic impact	Social impact on local communities => sustainable economic development and welfare

Regarding the production of synthetic fuels based on renewable hydrogen, all the chemical conversion steps should also follow the sustainability logic. For example CO₂ for synthetic methane should not have anthropogenic origins, and be extracted directly from air (DAC).

CertifHy

Originated from the EU, the hydrogen sustainability scheme CertifHy is gathering stakeholders from research centers, industries and government in order to develop and establish the

Guarantees of Origin (GoO) certification scheme at the national regulatory level. CertifHy includes sustainable assessment on the life cycle of the GoG scheme (audition of production H₂, certification of relevant hydrogen associated events, trade and utilization of certificates). (Jensterle, Narita, Piria, Samadi, et al., 2019)

The framework defines two types of environmentally friendly hydrogen: green hydrogen and low-carbon hydrogen. Green hydrogen is generated by renewables (hydro, wind, solar and biomass energy). Low-carbon hydrogen, according to CertifHy, can also be produced by non-renewable energy sources, such as nuclear or by fossil fuels combined with CCUS. The CertifHy eligible criteria regarding *the GHG reduction levels* for green hydrogen, as well as for low-carbon hydrogen should be 60% compared to the same amount of energy of natural gas. The natural gas threshold is defined as 91 g CO₂/MJH₂, therefore, hydrogen produced should contain no more than 36,4 g CO₂/MJH₂. (Jensterle, Narita, Piria, Samadi, et al., 2019) In the case of nuclear-based hydrogen the GHG emissions are at the same level with wind-based hydrogen. However, the nuclear waste is an environmental threat and, in order to provide fair certification label and differentiate yellow from green hydrogen refers to the low-carbon hydrogen. Moreover, some additional costs referring to the nuclear waste management could provide the difference in a monetary terms.

On Figure 43 the CertifHy GoO Process is illustrated. The principle is similar to the green certificated for the electrical energy. The CertifHy certificates become available and are traded independently from the production site within the EU territory. The GoO hydrogen certificate is an electronic document that proves the emission free origin of the gas. The information gathered in the e-document contains type of H₂ (green or low-carbon), energy source, GHG emission intensity, production site and time of the production. According to the authors, hydrogen without GoO is classified as grey (mix with the conventional fuel based H₂)

The CertifHy Process

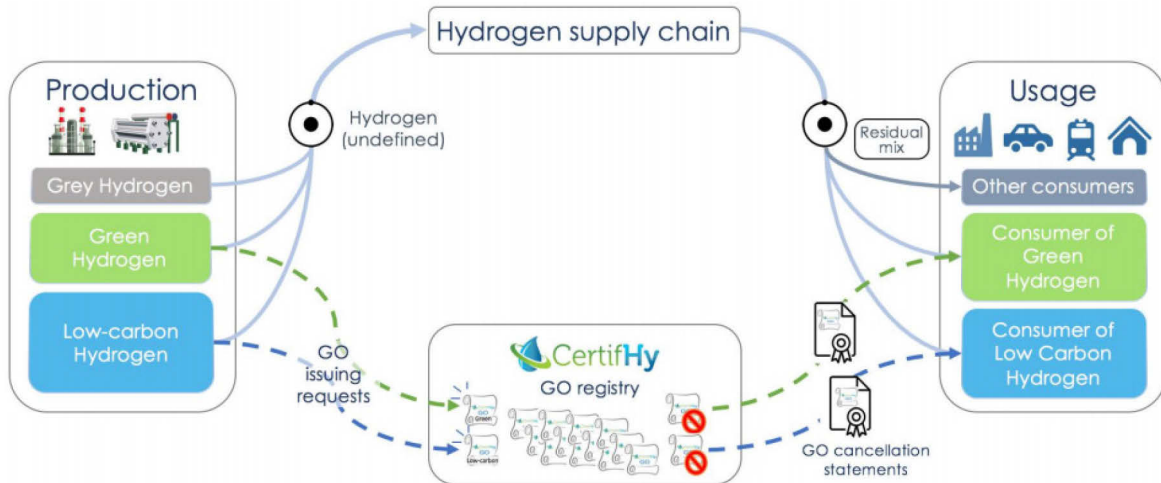


Figure 43. CertifHy GoO Process. (CertifHy, 2019)

The project CertifHy is one of the candidates to become the main legal EU scheme of assuring hydrogen on GoO and become a starting point for an establishment of cross-border trade. When “trying on” CertifHy scheme on the bilateral cooperation of Russia and Germany, the question arises, whether Germany will accept the nuclear-based hydrogen. The nuclear phase-out of Germany in 2022 speaks against the idea of nuclear-based hydrogen. Would Germany close their eyes in the beginning of the transition phase to the hydrogen economy and accept cost-efficient low-carbon hydrogen? What would be the conditions for the compromise? These questions need further investigation. Nevertheless, the remaining options, hydro and wind based hydrogen, have all the right qualities to gain “premium” status.

4.4 Obstacles and challenges for the implementation of the hydrogen economy

Germany

The ambitious and popular discussion on a hydrogen economy in the end always come with “but”, as manifold barriers are preventing to reach the desirable market level. In the decarbonisation oriented countries such as Germany, renewable energy is highly appreciated and awarded. A couple decades ago barely anyone could imagine such an expansion of variable renewable energy generation and drop of LCOE for wind and solar that we are facing today in Germany and around the globe. It is crucial to oversee and assess the obstacles beforehand.

In Germany the barriers can be split into four groups: *technological, commercial, regulatory and social*. *Technological* barriers are considered to pose the least threat to scaling up, as in general all of the technical aspects regarding production, storage, infrastructure and transportation are well-known and have been proved by the pilot projects. Nevertheless, hydrogen storage (in compressed and liquid states) is still the area for further development in order to reach a better efficiency and minimize energy input. The distribution chain of hydrogen is another downside of hydrogen economy. In the heating sector end users have various appliances from domestic to commercial and industrial, therefore a wide spectrum of hydrogen tolerance. The sensitivity of the compartments of natural gas network is described in Chapter 3.

Compared to the other EU member countries, Germany has already developed a detailed *regulatory* framework, including laws, regulations, and standards. As all of the German legislation, the hydrogen regulation seems to be clear and straight forward. However, some of them are imprecise and can be misinterpreted, which can be confusing and unattractive for investment-decisions. Examples of gaps and uncertainties are listed below:

1. Identify the legal status of Power-to-Gas applications, in the way that they are not considered as the end energy consumers (and are subject to taxes and fees), but rewarded for the service that they deliver in balancing the grid and solving the storage problem. Introduce energy storage in the national energy legislation.
2. A European harmonised regulation for the safe injection of H₂ into the NG grid and infrastructure in total should be clarified.
3. Change the classification of small scale electrolyzers under the IED (Industrial Emissions Directive) that currently are considered as producers of chemicals on an industrial scale. The permitting process could be simplified, because the PtG installations would be out of the scope of the IED.

The *commercial* barriers are linked with billing processes of the gas for the end consumers. Due to different (lower) volumetric density of hydrogen, the meters will show the higher volumetric consumption for the same energy usage. Therefore, several adjustments to the billing meters

have to be adapted. This is important as well for *socializing* hydrogen technologies and making them more public friendly. The knowledge and understanding of hydrogen safety is another challenge, as currently hydrogen in most cases in society is associated with the Hindenburg disaster. Promotion of hydrogen as a green energy carrier is essential among the public, to increase the commercial interest and initiate new projects.

Russia

In Russia the background for development of the hydrogen economy is polar opposite compared to the German or the European. As was discussed in Chapter 3, the renewable energy sources, such as PVs and wind turbines are experiencing the renaissance period in Russia and there is no evidence if the expansion of RE will continue in the next decades. Therefore, the pathway for the establishment of a new market commodity will be entirely different from the western examples. The main target will be the international trade of hydrogen, and the minor target - the support of the domestic renewable systems. The challenges associated with the promotion of hydrogen are much higher, than in Germany. The hydrogen integration in Russia should start with the development of a solid platform for R&D, different stakeholders interested in investments, governmental support, which would lead to economic, political, social and environmental strong benefits.

The resulted hydrogen complex will cover different areas of development: *technological, commercial, regulatory and societal*. The technological pillar represents the urge for establishment of hydrogen associated technologies factories based on the experience of the global leaders. Foundation of the research laboratories and initiating international hydrogen pilot projects is an essential part, as well as enabling university exchange and creation of the new study programs on the electric-chemical storage, in order to prepare highly educated labour.

From the regulatory perspective, some changes (exclusions) in the design of electricity market schemes are necessary. The main compartment of the hydrogen cost depends on the electricity tariff. As was discussed in Chapter 3, the direct purchase of the electricity from the generation source would allow to minimize the end cost of hydrogen roughly twice compared to the usual

tariff for industrial consumers. This is the main and decisive obstacle, which would trigger the hydrogen market.

Since green and low carbon hydrogen are treated differently in Western countries, one of the requirements for deploying green hydrogen production volumes is to increase drastically the installed capacities of wind turbines in the north of Russia in the long-term perspective (after 2035). The development of green certificates schemes for electricity and gases aligned with the international standards can significantly simplify the trade, bare the trust and lead to the long-term cooperation with international consumers.

Conclusion and Outlook

This master thesis investigates an emerging economic sector – hydrogen, and draws a link between Russian and European (German) energy systems, by initiating yellow and green hydrogen trade. The thesis provides comprehensive literature review on the latest political, technical and economic updates of the Power-to-gas technologies in Europe and Russia and highlights the existing barriers and challenges for establishing of the hydrogen economy. The thesis consists of four chapters with specific goals and assumptions. In *Chapter 1* the geopolitical changes due to the new decarbonisation vector in the energy policy of the EU are discussed and a rationale for integration of hydrogen into the European energy system is justified. The focus of the master thesis is put on German “Energiewende”, as one of the main and influential green energy transformation examples. German shift to intermittent renewable sources has already shown small impact on the import of the fossil fuels, which is going to become more visible by 2030 and 2050. Hydrogen from Power-to-Gas can become a support system for balancing the variable renewable energy sources, such as wind and solar and provide long-term and seasonal energy storage. Moreover, hydrogen acts as a decarbonisation tool for the sectors, which are impossible to electrify (industry, heavy, marine and air transportation) and sector coupling, connecting for the first time together gas, electricity and heat sectors.

In *Chapter 2* hydrogen gas is introduced as an energy carrier and compared to the other conventional gaseous fuels, such as natural gas. Furthermore, in the chapter the technology Power-to-Gas is introduced, by providing its detailed overview of state of art and current R&D in Germany and in Europe. The process of electrolysis is the foremost in the PtG. Several types of electrolyzers are existing, however, in the master thesis the types such as water alkaline and Polymer electrolyte membrane (PEM) are only highlighted due to their availability on the market, potential in scaling up, high efficiency and economic factor. Additionally, Chapter 2 provides a detailed literature review on the hydrogen demand (total and by sector) in Europe and in Germany particularly. The findings tell that the hydrogen demand varies significantly: in case of Europe it stands in the range of 1.050-2.250 TWh, which represents up to 24% of the final European energy demand in 2050. German green hydrogen demand is in the range of 80-170 TWh and if including synthetic fuels based on hydrogen, the demand can rise up to 900 TWh,

which represents up to 35% of the final energy consumption in 2018 (225 Mtoe). In order to satisfy the high hydrogen demand, the export of H₂ should be initiated. Russia is one of the candidates for a successful production and trade of the green and low-carbon hydrogen starting from 2030.

The third and the central *part* of the master thesis is concerned with the analysis of the state of art of Russian energy system and development of the possible scenarios for green and low-carbon hydrogen export to Germany. It was found out that Russian energy system suffers from the unutilized energy generation capacities, which represents 20 GW in the winter season and 30 GW in summer season. The unrealized energy potential can be used for the production of hydrogen via electrolysis. The majority of power plants with low capacity factor are nuclear and hydro power plants. Among all regions of Russia, the North-Western region is chosen as the strategic platform, oriented in the production and export of H₂ to the EU. As a result, it was conducted that in 2050 the North-Western region of Russia can cover more than 10% of Germany's H₂ demand: 10-80 TWh, or 0.46-3.7 million tonnes of H₂. In order to analyse the chances of initiation of the hydrogen trade between Russia and Germany (The EU), the technical-economic analysis of the hydrogen supply chain Russia-Germany was conducted and levelised costs of hydrogen (LCOH) were calculated. Different supply chains were designed in this master thesis. Three energy sources were chosen for the production of hydrogen – nuclear, hydro and wind. Additionally, for each of the energy source three scenarios were applied: two of which represented the centralised production of hydrogen, located offsite from the harbour area with underground storage (salt caverns and depleted natural gas fields) or compressed storage in steel tanks, the third option was direct production of H₂ within the harbour area with following liquefaction of H₂ for the shipment. Maritime transportation of liquid hydrogen was chosen as the shipment method for all scenarios. Among all of the storage methods, underground storage of compressed hydrogen showed the lowest costs (for construction and operation), followed by compressed H₂ storage in steel tanks and liquid hydrogen. Nevertheless, the total LCOH shows the most cost-effective results in the case of the on-site of the harbour H₂ production with the direct liquefaction for shipment. This option is limited in the size of application. Due to the intense energy requirements for liquefaction process, the size of the facility cannot exceed the

shipment capacity, in order to find the cost optimal solution. The final results showed that LCOHs (production + liquefaction + transportation RU-DE) are already competitive with green hydrogen produced in Germany and it is opening a great opportunity for Russia to take a place in the global hydrogen market after 2030. Power-to-Gas technology includes highly energy intensive processes, therefore, in order to assess the role of the cost of electricity, three different electricity tariffs, which reflects the situation in the Russian electricity market, were included in the calculation and compared. In the best case scenario (lowest electricity price = 0,011 €/kWh, direct purchase) LCOH was from hydro power plant, representing 2.4-3.1 €/kg, followed by nuclear-based H₂ 2.9-3.7 €/kg and wind-based H₂ 6.1-7.5 €/kg. Industrial consumer tariffs (0,044 and 0,077€/kWh) increases LCOH twice fold, the electricity cost represents 60-90% of the total cost of H₂ instead of 35-40% with electricity tariff of 0,011 €/kWh. Such results give a signal for policymakers and governments for reduction of the electricity price for PtG application, in order to accelerate the growth of hydrogen economy.

Chapter 4, the final part finalized all the findings of the master thesis, and represented in the form of the hydrogen roadmap of Russia and Germany up to 2050. Moreover, barriers and challenges for the development of hydrogen economy in Germany and as well as in Russia were highlighted.

This master thesis serves as a detailed overview of the current situation on the green hydrogen technologies in the European Union and Russia and is one of the first who draws a line between these two energy systems in order to integrate hydrogen as a new commodity and a decarbonisation tool. The master thesis can be visualised as an umbrella, which covers all necessary areas for the further research, such as state-of-art of the green and low-carbon H₂ related technologies, their commercial status and political engagement. From the technological point of view, the processes of electrolysis, compression and liquefaction can be improved by increasing its efficiency and flexible operation rates of H₂ output. Moreover, the alternatives for transportation of liquid H₂, such as ammonia and liquid organic hydrogen carriers, have all the potential to take place in the H₂ supply chain. Hydrogen pipeline network, which was not covered in the calculations, is one of the main competitors of the maritime shipment of H₂ and could be in the future the most cost effective way to transport vast volumes of hydrogen. In terms of market site, the commercialization of H₂ technologies in the nearest future is an essential step,

as it could reduce the capital expenditure for the technology itself and attract more investments. Development of hydrogen infrastructure, for example retrofitting the natural gas networks, construction of the new pure hydrogen networks, refueling stations and fuel cell operating machines, is another pillar of the market establishment. The third area for hydrogen development is policies and regulation. The lack of proper legislative specification and requirements hinder the ramping up of the H₂ technologies, as it causing additional levies and fees. Additionally, hydrogen certification schemes, which can prove the low-carbon and green origin of the gas have to become internationally spread, which could allow to initiate a fair trade.

The study provided general analysis, on whether hydrogen produced in Russia could be more attractive from the economic point of view. Taking into account, that electricity price in Russia is significant lower, than in Germany, availability of unutilized power capacities, water availability and land, the H₂ partnership between Russia and Germany can establish long-term and solid bonding between the energy systems, where both sides can reap the benefits. This master thesis has shown the relevance of the results in order to attract attention and initiate further research.

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Appendix

Appendix 1

Global annual average investment in renewables by scenario (billion USD 2018)

	Stated Policies			Sustainable Development		Change 2018 vs 2031-2040	
	2018	2019-30	2031-40	2019-30	2031-40	STEPS	SDS
Renewables-based power generation	304	329	378	528	636	24%	109%
Wind	89	111	122	180	223	37%	151%
Solar PV	135	116	125	179	191	-7%	41%
End-use sectors	25	117	139	124	145	456%	480%
Total	329	456	517	652	781	57%	137%
Cumulative		5 477	5 166	7 829	7 802		

Note: Renewables for end-use include solar thermal, bioenergy and geothermal applications for heating

Appendix 2

Typical specification of alkaline, PEM and high temperature (solid-oxide) electrolyzers.

Specification	Unit	Alkaline ^a	PEM ^b	SOEs ^c
Technology maturity		State of the art	Demonstration	R & D
Cell temperature	°C	60-80	50-80	900-1000
Cell pressure	bar	< 30	< 30	< 30
Current density	A/cm ²	0.2-0.4	0.6-2.0	0.3-1.0
Cell voltage	V	1.8-2.4	1.8-2.2	0.95-1.3
Power density	W/cm ²	Up to 1.0	Up to 4.4	-
Voltage efficiency	%	62-82	67-82	81-86
Specific energy consumption, system	kWh/Nm ³	4.5-7.0	4.5-7.5	2.5-3.5
Partial load range	%	20-40	0-10	-
Cell area	m ²	< 4	< 300	-
Hydrogen production, system	Nm ³ /hr	< 760	< 30	-
Life time, stack	hr	< 90000	< 20000	< 40000
System life time	yr	20-30	10-20	-
Purity of hydrogen produced	%	> 99.8	99.999	-
Cold start up time	min.	15	< 15	> 60

Source: most of the data compiled and modified from ^{a,b} [Smolinka et al., 2011] and ^c [NEEDS, 2008] IEK-STE 2013

Appendix 3

Input data

Based on the data from The ASSET project, the European Commission, 2018

https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

Power Generation technologies	Overnight Investment Costs in a greenfield site excluding financial costs during construction time				Fixed Operation and Maintenance costs (annually)				Variable non fuel cost				Electrical efficiency		Lifetime	Capacity factor	Annual growth of O&M costs with plant age
	EUR/kW				EUR/kW				EUR/MW						years	%	%
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2050			
Onshore Wind (very high potential)	1200	1066	915	848	22	21	21	20	0,25	0,25	0,25	0,25	1	1	25	0,42	5
Nuclear III gen. (including economies of scale)	5300	5050	4750	4700	120	115	108	105	6,4	7,4	7,6	7,6	0,38	0,38	60	0,85	1,76
Run of River	2450	2400	2350	2300	25,5	25,5	25,5	25,5	0,32	0,32	0,32	0,32	1	1	50	0,22	5

Conversion technologies	Investment cost per unit of capacity			Fixed O&M costs per unit of output			Capital and fixed cost per unit of output			Variable, fuel and emissions cost per unit of output			Total LC per unit of output at 8,5% discount rate		
	EUR/kW - output			EUR/kW - output			EUR/MW - output			EUR/MW - output			EUR/MW - output		
	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate
PEM water electrolysis, centralised, large scale	1400	340	200	49	15	10	26,6	6,9	4,2	72,5	78	86	99	85	90
alkaline water electrolysis, centralised, large scale	1100	300	180	28	14	9	19,5	6,1	3,8	73	83	87	99	89	90
SOEC water electrolysis, centralised, large scale	1595	804	600	55,8	36,2	39	30,3	16,3	13,6	89,8	98,1	86,7	120,1	114,3	100,4

Refuelling technologies	Investment cost per unit of capacity			Fixed O&M costs per unit of output			Capital and fixed cost per unit of output			Variable, fuel and emissions cost per unit of output			Total LC per unit of output at 8,5% discount rate		
	EUR/kW - output			EUR/kW - output			EUR/MW - output			EUR/MW - output			EUR/MW - output		
	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate
H2 compression station	114	102	91	0,4	0,4	0,4	2,3	2,1	1,8	3,6	4,6	5,1	5,9	6,6	7
H2 Liquefaction station	761	635	457	23	23	23	12,1	10,6	8,4	1,1	1,4	1,5	13,2	11,9	9,9

Distribution technologies	Investment cost per unit of capacity			Fixed O&M costs per unit of output			Variable, fuel and emissions cost per unit of output			Total LC per unit of output at 8,5% discount rate		
	EUR/kW - output			EUR/kW - output			EUR/MW - output			EUR/MW - output		
	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate
H2 pipeline 60 bar	178	173	166	7	7	7	1	1	1	3,8	3,7	3,6
H2 pipeline 10 bar	723	723	723	29	29	29	4,2	4,2	4,2	25,2	25,2	25,2
Road transport of liquid H2	74	68	55	7	7	7	0,3	0,3	0,3	3	2,8	2,5
Road transport of gaseous H2	344	324	284	58	58	58	3,6	3,6	3,6	19	18,5	17,5
maritime transpotation												

Storage technologies	Investment cost per unit of capacity			Fixed O&M costs per unit of output			Variable, fuel and emissions cost per unit of output			Total LC per unit of output at 8,5% discount rate		
	EUR/kW - output			EUR/kW - output			EUR/MW - output			EUR/MW - output		
	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate	2015	2030	ultimate
Underground H2 storage	5340	3936	3821	0	0	0	0,6	0,7	0,8	2,8	2,4	2,4
Pressurised tanks	6000	4800	4659	0	0	0	0,6	0,7	0,8	3	2,7	2,7
Liquid H2 Storage	8455	6800	4000	0	0	0	0,7	0,9	1	4,1	3,6	2,6
Metal Hydrides	12700	11430	11271	0	0	0	0,5	0,7	0,8	5,7	5,3	5,3

Appendix 4

Results. The role of the system compartments in the total cost of hydrogen

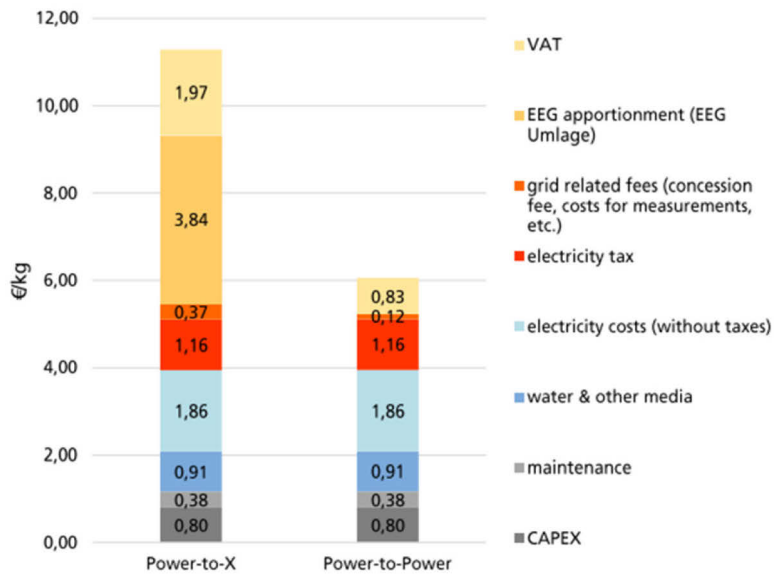
Nuclear	1 ruble/kWh; 10%	1 ruble/kWh						4 ruble/kWh					
	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	
Energy source	0,75	20%	0,75	22%	0,75	26%	0,75	11%	0,75	11%	0,75	13%	
Electrolyser (CAP)	0,14	4%	0,14	4%	0,14	5%	0,14	2%	0,14	2%	0,14	2%	
Electrolyser (O&M)	0,18	5%	0,18	5%	0,18	6%	0,18	3%	0,18	3%	0,18	3%	
Electrolyser (ELCO)	0,55	15%	0,55	16%	0,55	19%	2,21	32%	2,21	33%	2,21	37%	
Compression	0,42	11%	0,42	12%	-	-	0,48	7%	0,48	7%	-	-	
CH2 Storage	0,36	10%	0,05	2%	-	-	0,49	7%	0,21	3%	-	-	
Liquefaction	0,92	25%	0,92	27%	0,92	32%	1,21	18%	1,21	18%	1,21	20%	
LH2 Storage (ELCO)	0,36	10%	0,36	11%	0,36	13%	1,45	21%	1,45	22%	1,45	24%	
Total	3,68		3,37		2,90		6,91		6,63		5,95		

hydro	10%	1 ruble/kWh						4 ruble/kWh					
	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	
Energy source	0,19	6%	0,19	7%	0,19	8%	0,19	3%	0,19	3%	0,19	4%	
Electrolyser (CAP)	0,15	5%	0,15	5%	0,15	6%	0,15	2%	0,15	2%	0,15	3%	
Electrolyser (O&M)	0,18	6%	0,18	6%	0,18	8%	0,18	3%	0,18	3%	0,18	3%	
Electrolyser (ELCO)	0,55	17%	0,55	19%	0,55	23%	2,21	34%	2,21	36%	2,21	41%	
Compression	0,42	13%	0,42	15%	-	-	0,48	7%	0,48	8%	-	-	
CH2 Storage	0,38	12%	0,05	2%	-	-	0,51	8%	0,21	3%	-	-	
Liquefaction	0,94	29%	0,94	33%	0,94	39%	1,23	19%	1,23	20%	1,23	23%	
LH2 Storage (ELCO)	0,36	11%	0,36	13%	0,36	15%	1,45	23%	1,45	24%	1,45	27%	
Total	3,18		2,85		2,38		6,41		6,11		5,42		

wind	10%	4 ruble/kWh						7 ruble/kWh						LCOE wind, direct to electrolyser					
	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	Off-site + t	% of total	Off-site + u	% of total	On-site	% of total	
Energy source	0,38	5%	0,38	6%	0,38	6%	0,30	3%	0,30	3%	0,30	3%	4,91	46%	4,91	49%	4,91	54%	
Electrolyser (CAP)	0,30	4%	0,30	4%	0,30	5%	0,30	3%	0,30	3%	0,30	3%	0,30	3%	0,30	3%	0,30	3%	
Electrolyser (O&M)	0,18	2%	0,18	3%	0,18	3%	0,18	2%	0,18	2%	0,18	2%	0,18	2%	0,18	2%	0,18	2%	
Electrolyser (ELCO)	2,21	29%	2,21	32%	2,21	36%	3,87	36%	3,87	38%	3,87	43%	0,00	0%	0,00	0%	0,00	0%	
Compression	0,55	7%	0,55	8%	-	-	0,61	6%	0,61	6%	-	-	0,47	4%	0,47	5%	-	-	
CH2 Storage	0,85	11%	0,21	3%	-	-	0,98	9%	0,36	4%	-	-	0,67	6%	0,00	0%	-	-	
Liquefaction	1,60	21%	1,60	23%	1,60	26%	1,89	18%	1,89	19%	1,89	21%	1,20	11%	1,20	12%	1,20	13%	
LH2 Storage (ELCO)	1,45	19%	1,45	21%	1,45	24%	2,54	24%	2,54	25%	2,54	28%	0,00	0%	0,00	0%	0,00	0%	
Total	7,52		6,88		6,12		10,67		10,05		9,09		7,73		7,06		6,59		

Appendix 5

LCOH by HYPOS



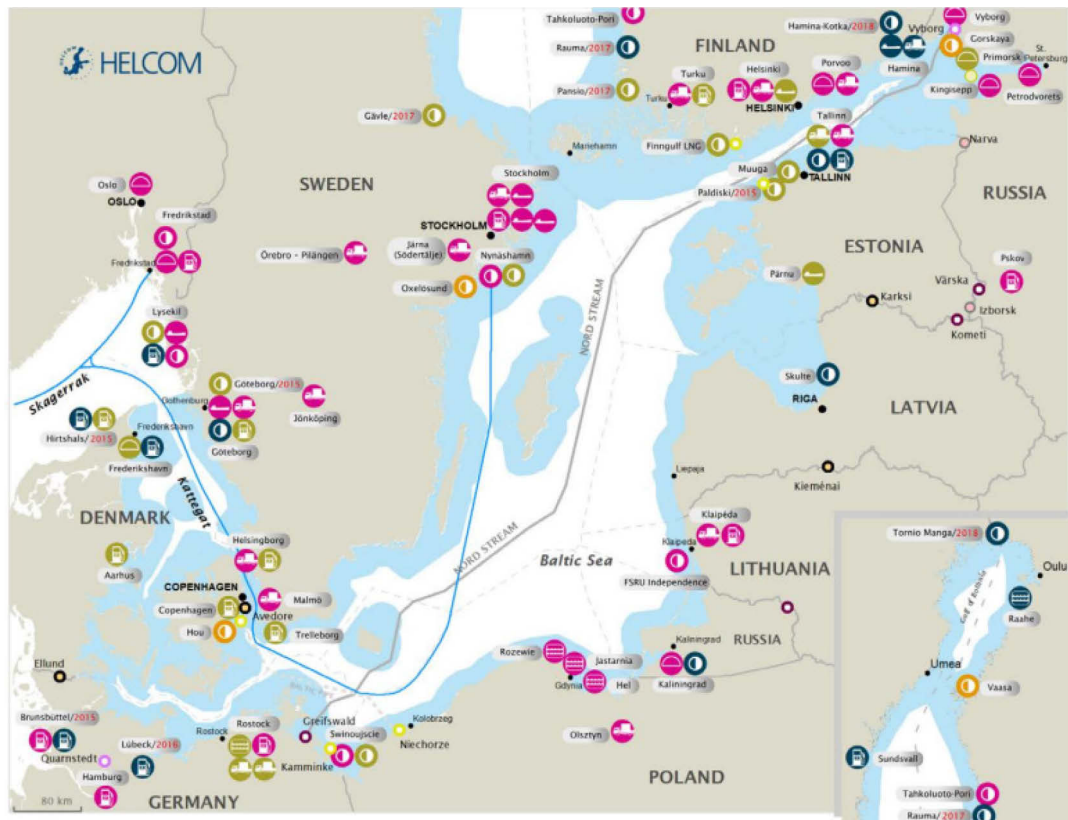
Input data: $\eta_{LHV} = 65\%$; $Invest_{spec.} = 1000 \text{ €/kW}$; planning costs = 5 m. €; amortization period = 20 years; degradation = 1,5 %/a; interest rate = 5 %; full load hours = 6000 h/a; electricity costs = 3,2 cent/kWh (\emptyset EEX Day-Ahead-Markt 2017); stack replacement = 10 years

Levelized Costs for Hydrogen (LCOH)

- ...for Power-to-X and Power-to-Power pathways
- ...@100MW_{el} PEM
- ... efficiency 65 % (LHV)
- ... 6000 full load hours per year
- ... specific invest 1000 €/kW

Source: (HYPOS, 2018)

Appendix 6. Map of the Baltic Sea. Source (HELCOM, 2019)



Small Scale LNG Infrastructure

● in operation
 ● under construction
 ● planned
 ● under discussion

○ ○ ○ ○ LNG import terminal offering new LNG services
○ ○ LNG liquefaction plant / liquefaction station
○ ○ ○ LNG bunker facility for vessels / fuel loading ship (on-shore)
○ ○ LNG bunker ship (off-shore)
○ ○ LNG refuelling station for trucks / fuel loading road
○ ○ ○ LNG satellite storages (not included in map)

○ City/YEAR
 ○ City, Start-up date

○ Cross-Border EU or non-EU export Under construction or Planned
○ Intra-country or intra balancing zone point
○ Non-EU Cross-border interconnection point
○ Cross-border interconnection point with non-EU third country (import/project)
○ Cross-border interconnection point
○ LNG Export Terminal - Project

Transport by tanker

— Indicative LNG route

--- EEZ borders
■ Territorial Waters