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From Vision to Reality: Evaluating the Practicality of Hydrogen Adoption in Poland

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Abstract

This work explores the evolving landscape of hydrogen technology in Poland's journey towards decarbonization. Situated within the broader European Union context, the study examines the diverse challenges and strategic imperatives shaping Poland's hydrogen economy. At the EU level, there is a significant push towards decarbonization, highlighting hydrogen's integration across various economic sectors. Poland's implementation of its Hydrogen Strategy emphasizes national efforts to comply with EU directives. Using the Multi-Level Governance framework, the study identifies key actors related to Polish hydrogen market development and their roles in overcoming barriers to foster a robust hydrogen ecosystem. The study emphasizes the importance of regulatory alignment, infrastructure development, the roles of private and state-owned companies, responsibilities across different levels of governance, and educational initiatives necessary to accelerate hydrogen adoption and realize its potential in Poland's sustainable future.

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List of Acronyms

AFIR (Alternative Fuels Infrastructure Regulation)

CCS (Carbon Capture and Storage)

CHP (Combined Heat and Power plant)

CEF (Connecting Europe Facility)

CF (Cohesion Fund)

EHB (European Hydrogen Bank)

ERDF (Regional Development Fund)

ETS (EU Emissions Trading System)

EU (European Union)

IPCEI (Important Projects of Common Interest)

MLG (Multi-Level Governance)

NCBiR (National Centre for Research and Development)

NFOŚiGW (National Fund for Environmental Protection and Water Management)

NPS (National Power System)

PCEI (Projects of Common Interest)

RES (Renewable Energy Sources)

RFNBO (Renewable Fuels of Non-Biological Origin)

RRF (Recovery and Resilience Facility)

TEN-E (Trans-European Energy Networks)

TSO (Transmission System Operator)

Introduction

The urgent need to tackle climate change and transition to renewable energy sources (RES) has become a major point of public discourse for a long time. Substantial and continuous initiatives are being made to develop clean energy sources while phasing out fossil fuels. One of the most significant drivers of those actions was the signing of Paris Agreement by 196 countries in 2015, binding them to combine efforts and limit the global warming by 1.5 °C by the end of the century. The development of wind energy, photovoltaic farms, the use of biomass for energy purposes or hydroelectric power plants is growing year by year. Along with this growth, new problems associated with integrating these sources into energy systems are becoming increasingly apparent.

Achieving total decarbonisation with the use of RES raises questions about the ability of the new system to ensure energy security, relying on variable generation, dependent on weather conditions or geographical availability. This inability of RES to guarantee generation at times of high demand risks a black-out, and over-generation at times of low energy demand puts great stress on electricity grids. In addition, hard to decarbonise industries such as steel and concrete require an alternative to electricity. The use of hydrogen as a new energy carrier offers an opportunity to solve the problems mentioned above.

Hydrogen is a gas that occurs in the atmosphere in the molecular form of H2 and usually is bound to other compounds. Therefore, various processes such as pyrolysis, gasification or electrolysis are used to obtain it in the pure form. Depending on the method used to produce hydrogen, different emissions levels are released, and different fuel types or energy sources are required. A colour system was adapted to distinguish the origin of the hydrogen (fig. 1). Black, grey, and brown hydrogen, which production requires fossil fuels (coal or natural gas) is associated with higher CO2 emissions.

It is significant to note that currently, 91% of hydrogen produced in Europe is emissive and this share worldwide is even bigger (fig 2). When CO2 emissions are being captured during the production process by carbon capture and storage (CCS) systems, hydrogen produced is labelled as blue. The most desirable type of hydrogen, for which there is the greatest demand, is low-emission hydrogen. Exact definition when hydrogen can be called “Renewable” in European Union can be found in Delegated Act on a methodology for renewable fuels of non-biological origin (RFNBO).[1]

Hydrogen labelled as low carbon includes colours such as yellow, pink and the most desirable green. Green hydrogen is produced during the process of water electrolysis. In this energy-intensive process, the H20 molecule is split into hydrogen (H2) and oxygen (O2). High demand for this hydrogen type result from lack of emissions during its production process. Other advantages of this production method include closed water cycle during hydrogen utilisation (the derivative of hydrogen oxidation is water: 2H2 + O2 = 2H2O) and the possibility of using various RES for its production. Due to that, green and low-emission hydrogen (hereafter referred to just as hydrogen in this paper) has gained worldwide interest.

Hydrogen strategies have already been introduced in 43 countries around the world (fig. 3) and the market for that energy carrier is expected to significantly grow in the coming years (fig. 4). In terms of geopolitics, development of hydrogen creates an opportunity for some countries to become an energy exporter (table 1). Examples of such countries include Chile, Morocco, or Namibia. For others, like most states of European Union, Japan, or South Korea, import of H2 will be necessary to meet anticipated market needs. Confirmation of the importance of hydrogen technology in the future energy mix was also evident in the policies adopted in the United States in 2023. Additional support for the development of hydrogen technologies and Regional Clean Hydrogen Hubs in the US has been established at 7 billion dollars.[2] Huge interest in development of green hydrogen can also be seen in China, where renewable hydrogen capacity is expected to reach 100 GW by 2030.[3]

Interest in hydrogen by the global superpowers is not only motivated by its potential to help mitigate climate change. Some people also recognise hydrogen as one of the main drivers of the future economy, which will be necessary in the long term to maintain country's position in the race for geopolitical supremacy in the world.

It should be mentioned that hydrogen technology nowadays is not ready to meet all the objectives set for it. There are many technological, economic, and social barriers facing the implementation of hydrogen technology, causing many experts to be sceptical about the heralded great development of this sector. While hydrogen presents a potential answer to numerous decarbonization challenges, the technology is not yet advanced enough to achieve all of the highly ambitious goals. Challenges associated with hydrogen technology pertain to various aspects including technological, financial, safety, and regulatory issues. [4], [5], [6] To overcome these challenges, efforts are being made to increase efficiency of technology, develop infrastructure as well as implement hydrogen supporting policy and market design. Although hydrogen technologies are not yet developed enough to solve all the problems of today's energy sector, their potential is not being ignored.

In European Union (EU) hydrogen technologies are being pursued due to its low emissivity and potential to decarbonise different sectors of economy, for example transport, power and heating sector or energy-intensive industries. Especially in case of industry, hydrogen is seen as a mean to stop the process of offshoring. Companies are relocating their facilities from the EU to cut expenses.[7] They decide to move production to countries with lower wages, less stringent regulatory frameworks, and no additional emissions taxes. The negative consequences of this trend include an economic downturn and shrinking workplaces. Usage of hydrogen can allow industry sector to decarbonise while maintaining production and workplaces in Europe.[8]

The challenges facing the European Union are vast, and in the face of a global climate crisis, decarbonisation takes centre stage. As the third-largest hydrogen producer in the European Union, Poland can play a significant role in the implementation of the EU's energy transition objectives and EU's hydrogen strategy. It is crucial to replace grey hydrogen produced in Poland with green hydrogen and pursue its use to reduce emissions in different sectors of the economy. Creation of low-emission hydrogen market in Poland poses a major financial, organisational, regulatory, and technological challenge. New hydrogen industry must be based on RES and efficient electricity transmission system as well as meet specific conditions of various interconnected or independent sectors of the economy. However, the transition towards hydrogen technology can be beneficial to the country's interests. Investment in this sector can facilitate the decarbonisation of the Polish industry, transport, or power and heat generation, thereby preventing the country from falling behind the rest of the EU in terms of technological advancement.

This paper shall explore potential and current obstacles for hydrogen technologies development in the EU and Poland. The significance of this emerging sector lies not just in complementing existing RES technologies, but rather to being a key pillar of the future energy system, enabling the successful achievement of energy transition.

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Figure 1: Hydrogen Colour Spectrum in Relation to Production Method and Emissions.[9]

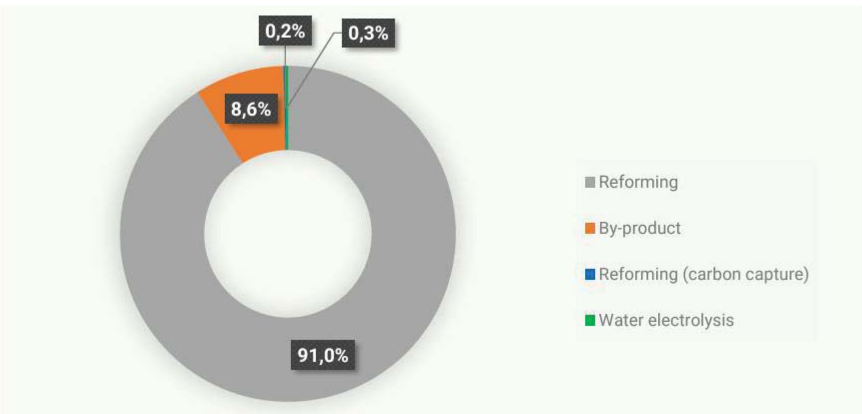

Figure 2: Hydrogen Production Capacity by Production Process in 2022.[10]

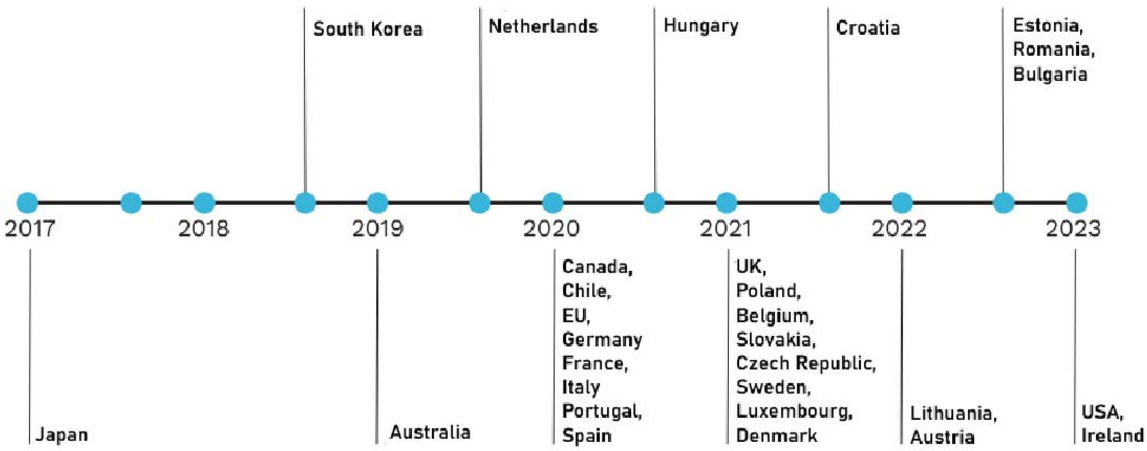

Figure 3: Timetable of Publication of Selected Hydrogen Strategies.[11]

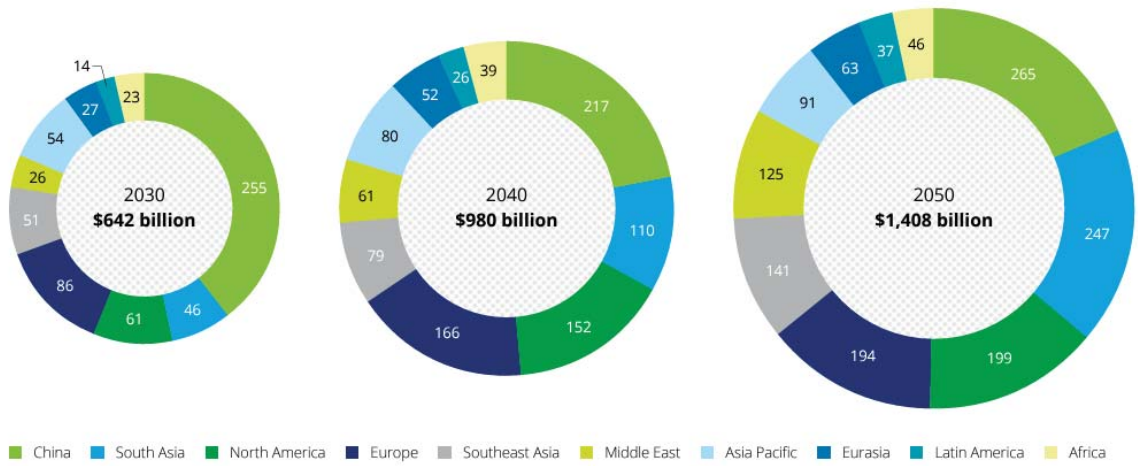

Figure 4: Global Clean Hydrogen Market Size Estimations.[12]

Table 1: Analysis of Potential of Hydrogen Export in Chosen Countries.[13]

#	Group	Resource endowment: Renewable energy resources	Resource endowment: Renewable freshwater resources	Infrastructure potential	Example countries
1	Export champions with vast renewable energy and water resources, as well as high infrastructure potential	++	+	+	Australia, United States, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	++	−−	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	−	+	+	Parts of the EU, Japan, South Korea
4	Resource-rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Resource-rich countries with low infrastructure potential	+	+/−	−	Most parts of South America

Legend: Abundant/very high (++); Available/high (+); Poorly available/constrained (−); Scarce/highly constrained (−−)

Research Question

Given the importance of the hydrogen revolution, which is gaining momentum around the world, the aim of this work is to answer the question:

Do existing policies and ongoing initiatives support the practical implementation of low-emission hydrogen technologies in Poland, considering the guidelines of the European Union Hydrogen Strategy and the realities of the European hydrogen market? – A policy and market analysis

The first chapter examines the dynamics of the European market, highlighting current trends in renewable energy sources (RES) and the driving forces behind hydrogen development within the European Union. It traces the evolution of European hydrogen policy, with a particular focus on the EU Hydrogen Strategy and analyses the key obstacles to the implementation of hydrogen technology in Europe, alongside the measures being taken to address these challenges.

The second chapter shifts to the current hydrogen policy and market landscape in Poland. It outlines the market conditions that are fostering the growth of the low-emission hydrogen sector in Poland. Building on insights from the first chapter, the Polish Hydrogen Strategy is evaluated in the context of the EU Hydrogen Strategy's guidelines. The chapter also reviews and assesses the various European and national funding options available for hydrogen projects in Poland, examining their alignment with the strategic objectives of the European and national hydrogen strategies.

The third chapter provides a comprehensive overview of the current developments across the entire value chain of the low-emission hydrogen market in Poland, identifying key players and stakeholders involved. It examines the roles of regional and local governments in supporting hydrogen technology, as well as analyses existing and potential future barriers to hydrogen development in Poland.

Methodology

To appropriately assess the impact of policy on the development of hydrogen market, while taking into consideration the potential of a technology in Poland, this thesis adopts a Multi-Level Governance (MLG) methodological approach. Subject matter relates to many interrelated areas, like policy, economy, market conditions and social aspects. The framework facilitates a thorough evaluation of the distribution of responsibilities among relevant stakeholders across various levels of governance, including the European Union, national and regional governments, private and state-owned hydrogen companies, non-governmental organizations, and civil society. It draws a broad picture of actors who have authority and competences to make binding decisions in the topic of hydrogen or have means to drive the change forward. Multi-level governance is the framework which can give the holistic view on the process of hydrogen market development as it not only focuses on the main participants of the market and their ability to make a difference but considers the power structure both vertically and horizontally which represents a multi-level and multi stakeholder governance approach. Some of the well-known researchers who have dedicated themselves to the popularisation and development of MLG methodology include Liesbet Hooghe and Gary Marks[14], Henrik Enderlein, Sonja Wälti and Michael Zürn[15] or Ian Bache and Matthew Vincent Flinders[16]. In their work, they explore various definitions and applications of MLG framework among different disciplines of Political Studies.

In the case of Poland, this approach involves consideration of the European Union's hydrogen guidelines, the Polish Hydrogen Strategy and legislation, contributions from regional governments, public and private energy companies' investment strategies, the state of the energy transmission and distribution sector, hydrogen valleys and hubs, and the public opinion. MLG can help to understand distribution of competencies in regard to hydrogen market development between different levels of Polish administrative structure – national government, voivodships ("provinces"), powiats ("districts") and gminas ("municipalities"). [17] To assess market condition and hydrogen development potential in those sectors, interviews with hydrogen experts related with different, mentioned above fields were conducted. References to expert statements are used throughout the work, with the entirety of the interviews available in the appendix.

Table 2: Overview of Conducted Interviews with Experts.

Interview number	Category	Role
1	Hydrogen Business Organisation (PL)	Hydrogen Valley Coordinator
2	Environmental Agency	Scientific Associate
3	Industry	Junior Professional
4	Industry	Gas Market Expert
5	Regional Government	EU Funds Management
6	Industry	Expert in Hydrogen Transport Sector
7	Hydrogen Business Organisation (EU)	Hydrogen Regulatory & Market Intelligence
8	Industry	Hydrogen Technology Expert
9	Industry	Alternative Fuels Expert
10	Industry	Hydrogen Project Manager
11	Academia	Research

Chapter 1: Evaluating the EU Hydrogen Market

This chapter is dedicated to analysis of hydrogen market development potential within the EU context. The current state of the RES and hydrogen markets in the EU, along with their potential for future growth, is being assessed. Evolution of European hydrogen targets over the years and EU Hydrogen Strategy are analysed. Limitations to hydrogen technologies development and possible actions to overcome them are highlighted. From an MLG perspective, this chapter focuses on the reality of hydrogen market development in Poland through the lens of the supranational level of governance.

Evolution of Renewable Energy and Hydrogen Development in Europe

Analysis of the green hydrogen market development in any market environment shouldn't be done without the consideration of RES capacity and generation potential. In Europe the share of energy generated from clean energy sources has had an upward trend over the years. For the year 2022 European Union achieved 23% share of energy generated from RES in final energy consumption, which shows how much more work needs to be done to achieve climate neutrality goals set for 2050 (fig. 5). However, considering only power generation sector, we can see that the share of energy generated by RES is much higher and emissions in this sector almost halved since their peak in 2007 (fig. 6).[18] More than 40% of electricity is generated by renewables and share of power originated from fossil fuels represents only around 30% of EU's energy mix. This indicates that statements about moving away from fossil fuels are not merely visible on paper, but action is being taken and is achieving tangible results. Fossil fuels are being systematically phased out from Europe, especially coal which consumption is decreasing notably over the years (fig. 7).

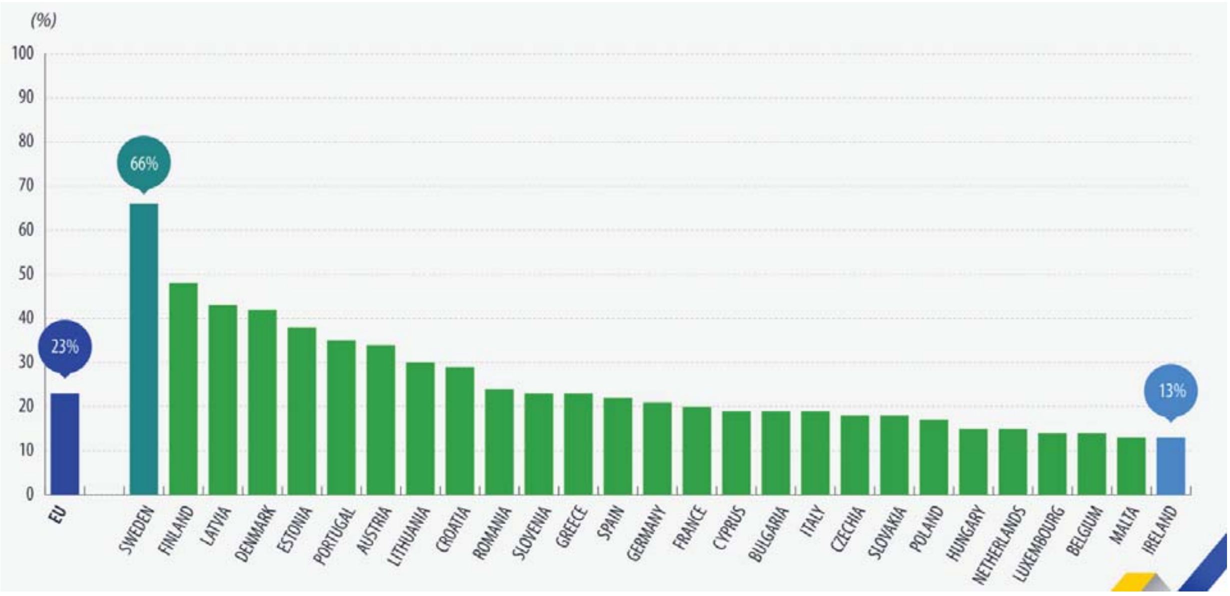

Figure 5: Overall share of energy from Renewable Sources in 2022. [19]

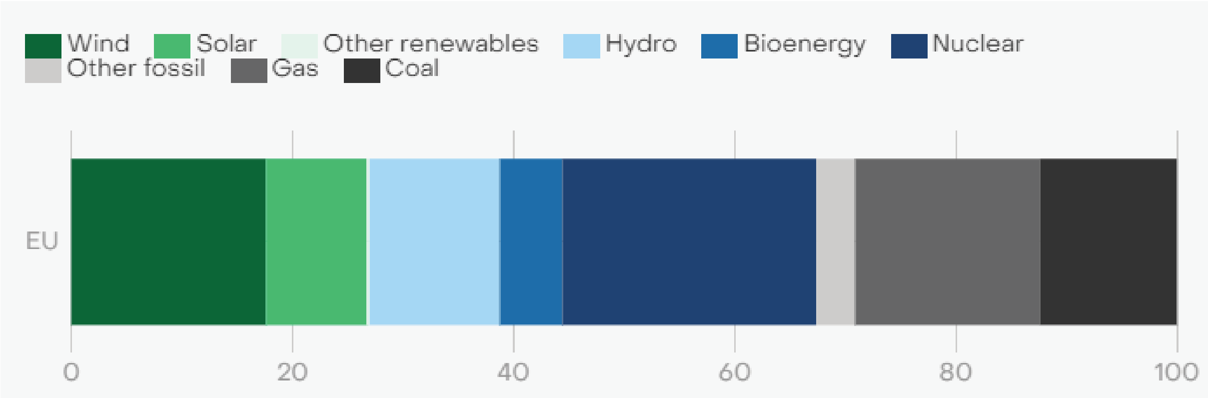

Figure 6: European union share of electricity generation by source 2023. [18]

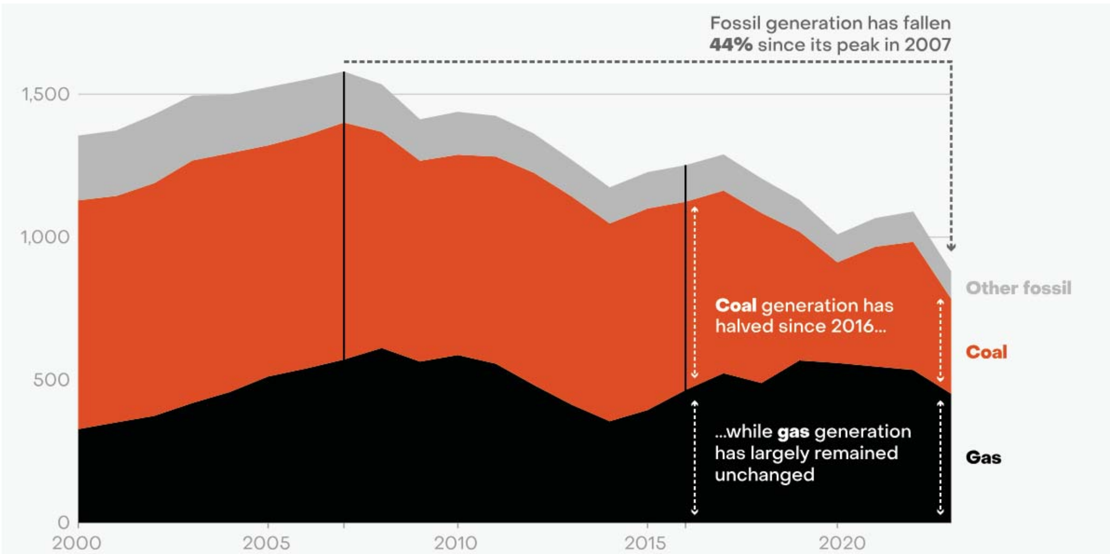

Figure 7: Share of power generation using coal over the years (TWh). [18]

With the move away from centralised energy production taking place in large power plants come new problems. Old fossil fuel-based sources are often located next to large industrial centres or cities requiring a large supply of energy. Unfortunately, they not always can be easily replaced by RES due to issues with land use, requirements in terms of weather conditions or environmental concerns. RES are being built in places where they generate most of energy. It means they sometimes must be located further from the places where the electricity is needed. That puts great stress on the electricity grid, which now must be capable of transmitting energy for much longer distances. Moreover, RES generate power in an uncontrollable manner. Lack of generation or over generation – both daily and seasonally – makes balancing of the grid even more challenging (fig. 8). The primary consequences of this issue are grid curtailments, the lack of approval for the connections of the new RES to the grid, or the disconnection of RES from the grid during periods of excessive energy production in the system.[20] These issues are becoming increasingly common. As a result, despite significant decarbonisation pressure from the EU, achieving ambitious net zero emissions targets by 2050 will be unattainable without the use of hydrogen. [Interview 7] Solely curtailments resulting from wind generation in EU are expected to reach over 9.3 TWh in 2030.[21] The considerable energy losses and inconsistency in power generation result in fluctuations on the electricity market and force implementation of relevant countermeasures. Investments in the development of transmission networks are being pursued, which can’t solve the entirety of the problem and unfortunately is not always possible, due to expansion grid restrictions. Secondly, new energy storage projects become increasingly economically viable and are starting to be crucial for the correct functioning of the energy system. As we move away from a fossil fuel-fired based load and rely more on variable RES generation, the need and opportunity for new solutions arises.[22] Hydrogen is becoming one of the significant and prosperous solutions to modern energy system problems (table 3). As RES become increasingly prevalent, the potential for hydrogen market development increases. Negative prices of energy due to over-generation of RES are becoming more common. The idea to secure the leakage of green energy for electrolysis purposes will give at those times presumably higher levels of return than the energy market itself. The production of hydrogen by electrolysis is a highly energy-intensive process, which affects its price. It is the large amount of new renewable energy capacity, which is being installed, that is making hydrogen more competitive.[Interview 8] Moreover, hydrogen also offers a possibility for electricity generated from renewable sources to be used in new applications, like green gas, green chemical and green fuel.

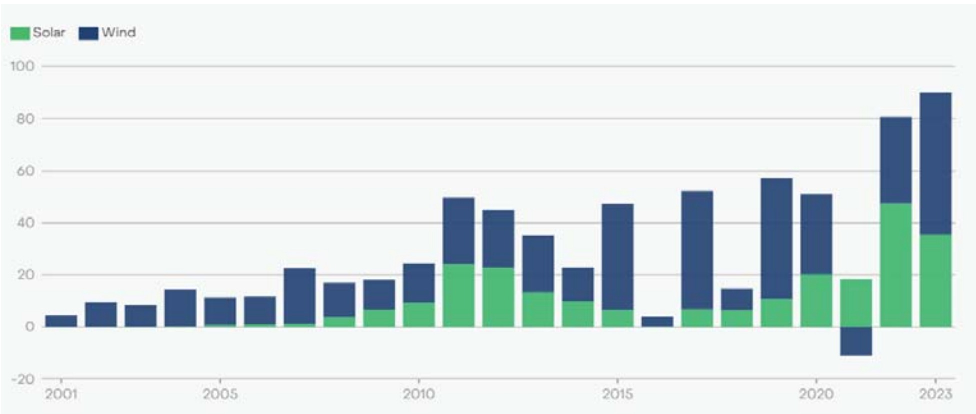

Figure 8: Annual change in power generation from wind and solar over the years (Twh). [18]

Table 3: Comparison of sector coupling and storage technologies for grid balancing. [23]

Options for stabilizing RES system		Suitability (Intra-day / Intra-month / Seasonal)	Assessment	Suitability for long-term storage?
Over-supply	Reduce supply	Shut down RES	• Technically feasible • Inefficient, losses of investment	✗
	Sector coupling	Power-to-material (P2M)	• No reconversion to power possible • In R&D stage	✗
		Power-to-gas (P2G)	• Technically feasible in number of use cases • Currently high investment cost	✓
		Power-to-heat	• Efficient, discharge only to heat (not power) possible • Suitable for short-term balancing only	
	Store and discharge	Power-to-gas-to-power (P2G2P)	• Reconversion possible • Low full cycle efficiency • Only if P2G not suitable/sufficient	✓
Under-supply		Battery; Compressed air, flywheel	• Technically feasible • Only short-term supply economically viable	✗
		Pumped hydro; Hydro reservoir (Scandinavia; Alps; ...) incl. interconnectors	• Limited storage capacity due to natural limitations	✗
	Reduce demand[1]	Demand side management (DSM)	• Consumption pattern only allows for limited shift within day	✗
	Increase supply	Structural renewables oversupply	• Technically feasible • Highly inefficient and capital intensive, losses of investment	✗
		Conventional backup (e.g., gas plants)	• Feasible if power generation is decarbonized (e.g., pre-combustion CCS)	

1 Demand reduction/demand balancing beyond expected structural demand reduction and efficiency gains (e.g., via energy-efficient renovations of buildings)

Currently, hydrogen produced in Europe is predominantly grey. Germany, the Netherlands and Poland lead in terms of generation capacity (fig. 9). Hydrogen is mainly utilised by refineries, the chemical sector or as a fuel for the industrial heat purposes. In 2022, the hydrogen market was strongly influenced by the increase in gas prices. This particularly affected demand in the ammonia industry, where hydrogen is a critical component with the greatest impact on total production costs. This has led to the closure of some facilities. Overall, however, the crisis has had little impact on the long-term shape of the hydrogen market.[10] One can surmise that it has led to more serious consideration of the possibilities of implementing renewable hydrogen and diversifying generation.

The potential for green hydrogen to be introduced into the energy mix of different sectors of the economy varies according to country's policy and stakeholders involved [Interview 7], economic conditions and the progress in research and development in different hydrogen technologies.

In power generation, hydrogen can facilitate energy storage and supplement RES production. It allows for utilising existing infrastructure like gas turbines in power plants. The heating sector stands to benefit from hydrogen's ability to produce heat in large CHP units for industrial or district heating purposes. There are also ongoing projects using hydrogen to heat individual households' estates. In transportation, hydrogen offers advantages over electric vehicles, particularly for heavy transport, due to its longer range and shorter refuelling time. It has potential to be a good fit for bigger machinery decarbonisation like ships, planes, agriculture and building machines, buses, or forklifts. In industry currently utilising hydrogen, low-emission hydrogen is a way to reduce emissions. Also, high energy-intensive industries, which involve high-temperature processes, can consider hydrogen as an alternative to fossil fuels.

We can speculate at what pace and how big will be the role of hydrogen in these sectors (fig. 11). Hydrogen's decarbonising potential, its applicability to a wide range of sectors and its ability to utilise the full potential of RES has led to hydrogen being described as the fuel of the future. A document which confirms the European Union's commitment to the use of hydrogen in sectors mentioned above and outlines the direction of development of hydrogen technology in Europe is the European Union Hydrogen Strategy. The arguments described above in this paper, explaining why we observe the development of hydrogen technologies, can be confirmed, and summarised by the quote from the strategy:

"There are many reasons why hydrogen is a key priority to achieve the European Green Deal and Europe's clean energy transition." [24]

Figure 9: Total hydrogen generation in Europe 2022. [25]

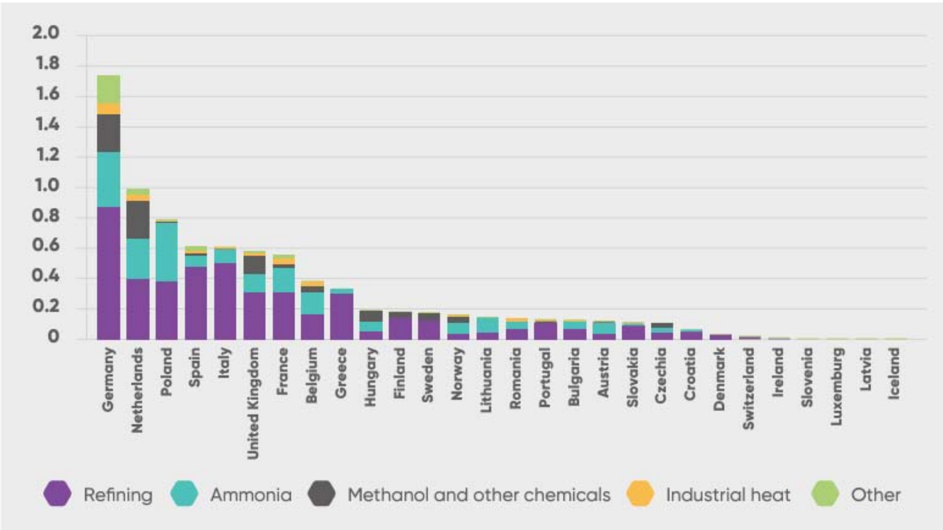

Figure 10: Hydrogen demand in Europe 2022 by end-use. [26]

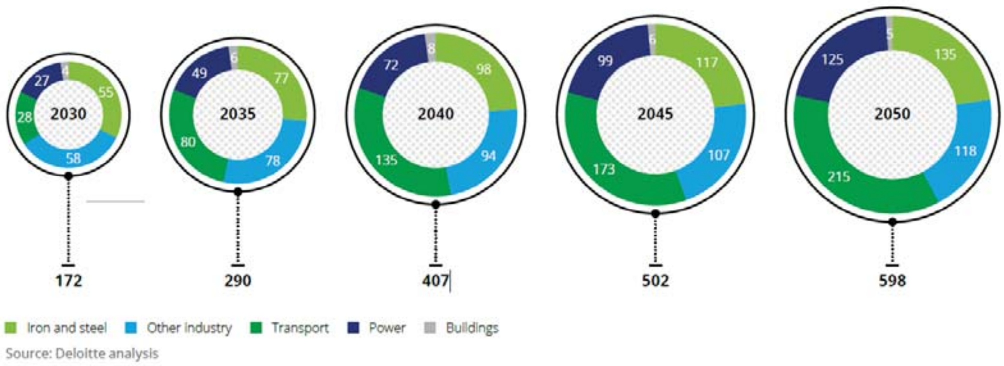

Figure 11: Evolution of clean hydrogen demand by sector (MtH2eq). [27]

European Union Hydrogen Policy Direction

The first, prominent document published by the EU, on the subject of hydrogen was the European Union's hydrogen strategy COM (2020) 301, in 2020.[28] It complemented the European Green Deal,[29] by aligning Hydrogen Strategy with the objectives of decarbonisation, RES development, circular economy, local production and energy security.

The Hydrogen Strategy is not a document that contains a precise description of the measures and actions to be implemented to achieve the objectives of the strategy. Rather, it provides an indication of the direction and sectors in which hydrogen technologies should be developed. Itself, it is not an inhibitor of hydrogen market development[Interview 8]. A concrete Policy Framework indicating the exact requirements and objectives for the use of hydrogen in transport and industry was presented in the Fit-for-55 package published in 2021. The Fit-for-55 also includes proposals and support for implementing a hydrogen market and constructing a hydrogen infrastructure.

The importance of hydrogen for the European economy, with particular emphasis on its role in ensuring energy security, was made particularly clear with the introduction of the REPower EU 2022 plan, published following the Russian invasion of Ukraine.[30] The plan, one of whose main objectives was to become independent of energy resources from Russia, dedicated one of its six main chapters (Hydrogen Accelerator) to hydrogen technologies. The European Commission proposed to increase the Hydrogen Strategy's targets for renewable hydrogen generation in the transport and industrial sectors from 5.6 Mt to 20 Mt of total EU hydrogen consumption by 2030 (fig. 12). 10 Mt of hydrogen should be produced domestically, other 10 Mt imported. It is estimated that around of 500 TWh of green electricity will be required to meet the 2030 RFNBOs production target.[31] This raises concerns and questions as to whether newly set, demanding targets are realistic within the given timeframe.[Interview 9] If hydrogen targets are considered to be too high, they will not be taken seriously and this could have a negative impact on the perception of the whole sector.[Interview7] However, what is evident from hydrogen legislation adopted in Europe over the years, is that the EU is doubling down on both renewables and hydrogen. It sees hydrogen as one of the key solutions to the challenges of tomorrow's energy system.

The European Union Hydrogen Strategy is the document indicating the direction of the hydrogen market development. The first, of the important elements which it contains, is the precise distinction between the different types of hydrogen. It introduced definitions of different types of hydrogen in respect of its origin. It allows investors and market participants to plan the investments in hydrogen technologies knowing what is the position of European Union towards each method of hydrogen production, based on the CO2 emissions associated with production process.[Interview 8] Strategy also points out which types of hydrogen should be developed in a given timeframe. It sets a clear target for the development of renewable hydrogen, but also recognises that low-carbon hydrogen will be needed in the short and medium term to accelerate emissions reduction and support future hydrogen market formation. European

Union Hydrogen Strategy is divided into 3 time periods, with objectives to be implemented by the end of each timeframe (fig. 13).

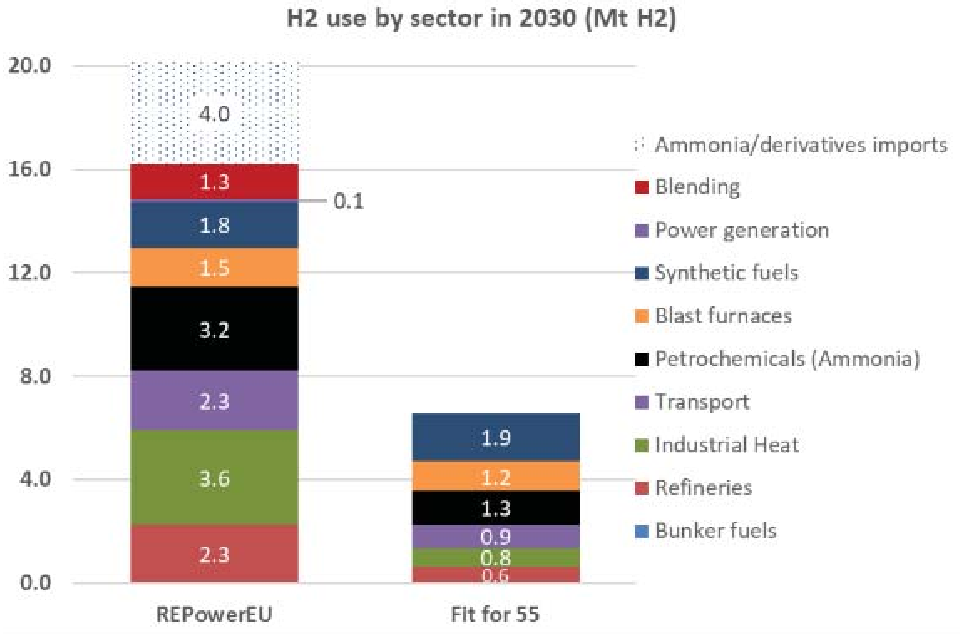

Figure 12: Hydrogen use by sector. [30]

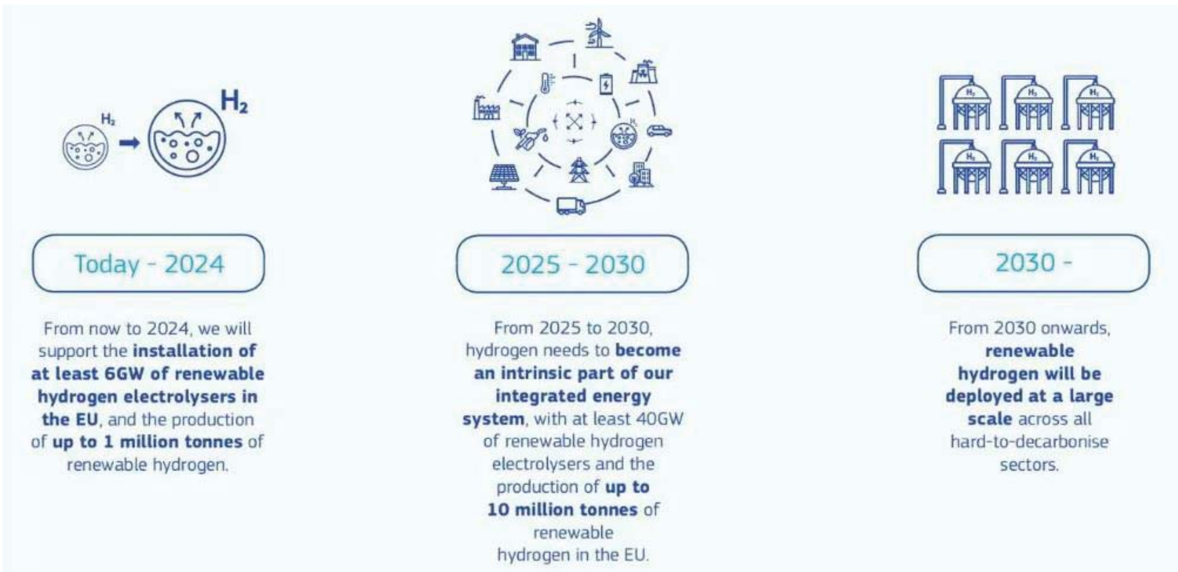

Figure 13: Phases of the European Union hydrogen strategy for a climate-neutral economy. [32]

The strategy's objectives are more precise for the short and medium term. More vague long-term targets present the state of the hydrogen market that the European Commission would like to achieve by 2050. The actions included in the strategy aim to scale up and achieve maturity of technologies of hydrogen production and utilisation while increasing the generation capacity of renewable hydrogen (especially via electrolysis). This would lead to the technically and economically efficient application of hydrogen in the economy, particularly in transport, industry, and hard-to-decarbonise sectors.

The strategy aims to deliver 6 GW of electrolysis capacity and an annual hydrogen generation level of 1 Mt by 2025 and 40 GW of electrolysis capacity and 10 Mt of annual hydrogen generation in 2030. These targets are not unattainable, in terms of potential for hydrogen production in the EU, however they are ambitious in terms of the time set for their implementation. The current maturity and reliability of hydrogen generation technology led experts to disagree on whether the objectives of the EU Hydrogen Strategy are achievable in the given timeframe. ("achievable targets"[Interview 7], "mostly achievable targets"[Interview 1], "achievable targets, not necessarily in a given timeframe"[Interview 9], "targets too ambitious in a given timeframe"[Interview 8]).

In addition, the strategy was created under the assumption that electrolysis costs will halve by 2030, which would increase the competitiveness of renewable hydrogen and drive the development of the hydrogen economy. Unfortunately, at this point, due to COVID-19 pandemic and the outbreak of war in Ukraine, the costs of the required materials and energy have increased,[Interview 9] rather than decreased. We are also observing problems with the finalisation of large capacity electrolyser projects (for both technical and economic reasons). [Interview 8]

Challenges Hindering the Development of Hydrogen Technologies in Europe

There are number of problems concerning hydrogen technologies at the moment. It is understandable, as the low-emission hydrogen market is just beginning to emerge and hydrogen molecule itself is hard to manage. To achieve decarbonization goals and develop the hydrogen market sufficiently to meet EU hydrogen targets, measures should be implemented to help overcome the challenges slowing down hydrogen development.

One of the main concerns at the moment is the price of hydrogen. In order for hydrogen to be competitive, the gap between costs of fossil fuels and hydrogen can't be that significant.[33] Current price of hydrogen needs to come down for hydrogen to be competitive on the market (fig. 14), It results in unattractive business model and too long payback period, which deters companies from investing in hydrogen production facilities. Moreover, it increases the operational costs of hydrogen fuelled technologies (cars, buses, gas turbines and engines etc.), which discourages consumers from buying them. Lack of demand for technology makes scale-up of production unfeasible and limits production capacities, which have direct impact on final costs of the products. Because of that, competitiveness of hydrogen technologies on the market is low and stops producers from scaling up the production.

Another issue, slowing down hydrogen market development, is stability of supply and demand. Many new low-emission hydrogen production facilities are currently under construction or in the planning phase. Basing strategic decisions on these facilities before they are commissioned entails risks. Especially in light of ongoing delays and hydrogen projects shutdowns.[Interview 8] Before hydrogen production market operates in big scale and is proven to be efficient and reliable, market participants will be hesitant to invest in technologies requiring hydrogen fuel. This idea works also the other way. It is hard to invest in production of hydrogen when you are not sure whether there will be a demand for your product. Because of this phenomena, current state of hydrogen technology resembles "Chicken-egg dilemma".[Interview 6]

Lack of infrastructure possess another challenge for hydrogen development. We are moving away from centralised production of hydrogen in big facilities based on fossil fuels in favour of more decentralized, smaller production systems. Without sufficient infrastructure, only small, fragmented projects are being developed with little connection between them.[Interview 7] Connecting producers with consumers is crucial to establish an efficient, large scale hydrogen market. Infrastructure is also needed in the form of hydrogen refuelling stations, which are necessary for development of hydrogen vehicles in transport. Limited places allowing for refuelling the vehicles have direct impact on technology attractiveness and prevents the widespread sale of hydrogen vehicles.

Current hydrogen legislation also poses some challenges in the EU. It varies from country to country, which makes international projects more difficult to implement due to different regulation and technical norms.[Interview 4] Some countries don't have a specific hydrogen law in terms of energy resource, which affects the time it takes to get permits and results in inconsistent projects authorisation process.[Interview 6] Vague and evolving hydrogen legislation with inconsistent policies at different levels of government adds to the uncertainty around hydrogen and makes it difficult for the market to develop. However, positive trends can also be seen, such as the Alternative Fuels Infrastructure Regulation (AFIR) requiring Member States to provide minimum refuelling infrastructure for alternative fuel vehicles, prompting hydrogen market development.

Importing hydrogen or its derivatives from overseas present even more challenges. The technical characteristics of hydrogen make it difficult to transfer H2 over long distances, due to losses. Moreover, it forces big invest in new specific infrastructure and vessels fleet. This raises concerns about feasibility and whether this is really the most energy efficient way to increase hydrogen supply.[Interview 7] Environmental issues such as land use, water scarcity or importing energy-intensive fuels from countries that have problems providing electricity to their own citizens raise questions about the morality of such actions. Importing hydrogen is also itself a difficult task, requiring additional efforts to bring together all the stakeholders, agree on technical, economic and strategic goals, which is logistically challenging.[Interview 3]

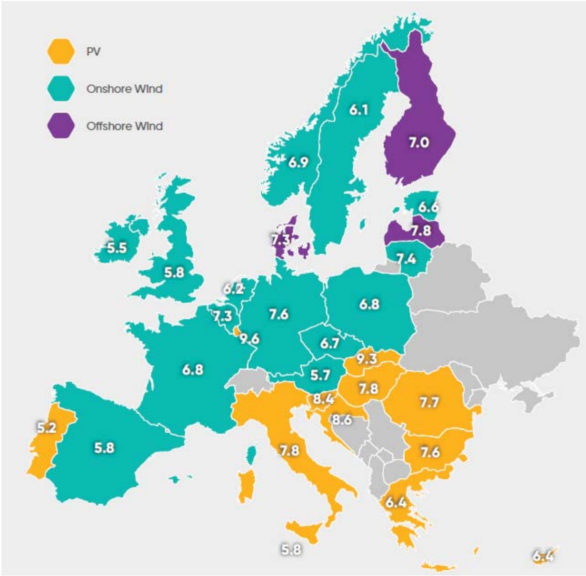

Figure 14: Average renewable hydrogen production costs in the Europe in 2022 (EUR/kg), using directly connected lowest-cost RES technology for a given country. [24]

Initiatives to Foster Hydrogen Market Development

Despite all these problems, there is a potential for hydrogen price drop in Europe.[Interview 1,7] Renewable electricity price is the biggest part of hydrogen production costs,[Interview 7] making the growth of RES capacity in the EU a major driver of hydrogen price reduction. The more RES capacity is going to be integrated, the cheaper the hydrogen is going to be. Already, we are experiencing very low or even negative electricity prices on the electricity market, during periods of favourable weather conditions. This trend is going to continue and magnify as EU pursues its net-zero targets. With more frequent and prolonged periods of high RES generation, producing hydrogen during these times will become more economically viable than selling electricity on the market, thus influencing hydrogen prices[Interview 8].

Additionally, there is also room for improvement in the electrolysis process itself. Although the costs of electrolysers have not decreased as rapidly as expected, some experts believe that they can still be reduced by 70-80% in the coming years.[Interview 7] Others argue that costs might increase due to rising component prices.[Interview 9] It should be said that electrolyser is not the most cost intensive element of hydrogen generation system. Some segments used are such as compressors are already well researched. Therefore, innovations alone may not be the sole reason for a future decrease in hydrogen prices[Interview 8]. However, some parts of the hydrogen generation systems are still new and while technology matures there are many prospects to improve efficiency. Achieving technology maturity will also mean, that contingency costs will be reduced, which currently hinder investments in hydrogen.[Interview 7]

There is also a room for improvement of energy management model used for electrolysis processes.[Interview 8] Each technology which enters the market, is in time perfected and this is true also for hydrogen generation. We can expect continuous technological advances in hydrogen technology as the hydrogen market develops. Resultant improvements in efficiency will lead to a decrease in the hydrogen generation cost and decrease in the hydrogen price itself.

Another factor which can have significant impact on the price of hydrogen and hydrogen technologies is scale up. While operating bigger system and introducing automatization processes, efficiency can be improved and price of final product reduced.[Interview 8] Larger investments allow also for implementation of "economies of scale",[Interview 9]for example, cost reduction by bulk purchasing of materials or spreading the fixed costs. This phenomenon applies both for technologies of hydrogen production and utilization. Scale up won't solve all the problems of hydrogen technologies [Interview 8] but as it will impact all the value chain of hydrogen, resulting price decrease of hydrogen and hydrogen technology utilisation will have significant impact on development of hydrogen market.

Over the years, increased generation of RES coupled with incremental technological advancements, improvements in energy management, business model optimization, and supply chain efficiencies, are expected to drive down hydrogen production costs, making the price of hydrogen no longer a barrier to the development of the hydrogen market.

The issue of stability and reliability of hydrogen supply is critical to tackle. Typically, as the supply increases, the price decreases. Therefore, if the EU's high hydrogen production targets are met, they are expected to positively impact hydrogen prices. The aforementioned scaling up of hydrogen generation technologies is one way to achieve this. Smaller electrolysis systems can be introduced in areas where the electricity grid cannot handle growing RES generation, contributing to increased production capacity. These systems can be installed in locations with frequent grid congestion or where new RES capacities cannot be connected to the grid.[Interview 1]

It's important to note that hydrogen production is not limited to electrolysis. Other methods are available, including those that utilize biomass, waste, nuclear power, or fossil fuels with CCS systems. These alternative production methods have the potential to significantly increase hydrogen supply and diversify production sources.

Among the various hydrogen production methods, producing blue hydrogen using fossil fuels with carbon capture and storage (CCS) is the most controversial. Its use wouldn't require significant changes to the operating grey hydrogen infrastructure (just the installation of CCS systems). It has the potential to reduce emissions and offers a controllable and cheaper alternative to green hydrogen.[Interview 8] However, blue hydrogen also has its drawbacks. The lower price of blue hydrogen may have a negative impact and discourage investors from pursuing green hydrogen production.[Interview 4] On the other hand, it is economically viable to invest in blue hydrogen only where natural gas infrastructure exists, because of the fact, that this infrastructure is already in place. That is mostly why blue hydrogen is cheaper. [Interview 8] This means that blue hydrogen may not have a significant impact on increasing the supply of hydrogen to the transport and synthetic fuels sectors, as new investment might be limited to just replacing grey hydrogen with blue, instead of building new capacities.[Interview 7]

Another issue with blue hydrogen is storage of CO2 captured during the production process, given the additional costs, potential leakage and specific conditions required for storage facilities. [Interview 8] Blue hydrogen also contributes to the continued use of fossil fuels and the maintenance of the associated infrastructure. Because of these drawbacks, most experts agree that blue hydrogen could help develop the hydrogen market, but only in the short to medium term, as a transitional source of hydrogen.[Interview 1,4,8] During that time we should pursue low-emission hydrogen systems allowing for controllable hydrogen production (example electrolysis with battery storage).[Interview 8] Later, when green hydrogen production will be sufficient, blue hydrogen could be phase out as the price gap between it and green hydrogen will decrease.[Interview 1] The role and relevance of blue hydrogen will also be determined by legislation at national and EU level, by setting a CO2 emission threshold for low-emission hydrogen production.[Interview 4, 7]

Different idea aiming to increase and diversify the hydrogen supply is the import of hydrogen and its derivatives from overseas. This is another way of increasing the pace of market development, which brings with it further problems. Hydrogen technology should not be pursued at the expense of local community's access to water or land. To achieve this, hydrogen projects must be done in accordance with just transition and sustainable development goals, based on the partnership relationship with exporting countries.[Interview 3] Amount of water needed for envisioned by EU Hydrogen Strategy hydrogen import demand will force producers to use seawater and desalinate it. These facilities can also support local water needs, if required.[Interview 7] Moreover losses accompanying the transport of hydrogen over the long distances favour the transport of ready-made materials (ammonia, jet fuel, methanol) which would be produced in the exporting country.[Interview 7] It means that hydrogen can contribute to creation of jobs for local community and bring significant tax revenues for exporting countries.[34]

Legislation is the important factor of hydrogen development. In order to stimulate the market, it needs to be consistent in Europe. It would allow for easier execution of international projects. On the EU level, corresponding hydrogen regulatory packages have been implemented in recent years.[Interview 4, 9]. Still, there are actions that can be taken which would benefit both hydrogen production (example correlation rules [Interview 7]) and hydrogen utilisation. Demand side policies would be beneficial to stimulate off-takers to invest in hydrogen and therefore make hydrogen production less risky.[Interview 9] A unified European Union legislation on hydrogen usage and standards across various sectors, to be adopted by all member countries, is an intriguing proposal.[Interview 1] It would enable the market to develop quicker, however national legislation lies within the competences of member countries.

Proper regulatory and legal framework as well as standardization of hydrogen usage are also one of the obstacles preventing operation of hydrogen market exchange. Nowadays, hydrogen is traded by bilateral agreements.[Interview 4] Introduction of hydrogen exchange would significantly improve hydrogen market formation process, providing transparency and reducing the hydrogen price by market mechanisms. Hydrogen exchange is expected to start operation around 2030, but for it to function properly, flexibility of the market has to increase, and necessary storage and transmission infrastructure have to be constructed.[Interview 4]

Infrastructure is the big factor limiting hydrogen development. Without it, costs of hydrogen transmission are too big, and connection of dispersed producers and consumers is difficult. [Interview 4,7,9] Financing is also posing the major challenge as costs of hydrogen projects are significant. Support of research, pilot, and commercialisation projects is necessary to stimulate hydrogen market development and to achieve EU's decarbonisation goals. Issues concerning hydrogen infrastructure and financing in the Polish market context are described in more detail later in this work (Financing – chapter 2, infrastructure – chapter 3).

Another approach to accelerate decarbonisation using hydrogen is blending, i.e. using a mix of hydrogen and natural gas in the current gas infrastructure. Many countries list blending as one of the objectives of their hydrogen strategies but doing it feasibly is difficult. Hydrogen transported through pipelines tends to leak. Network upgrades allowing higher hydrogen concentrations (above 5-15%) are expensive. On top of this, investments would have to be repeated every time hydrogen levels in pipelines were to be increased.[Interview 8] Due to the specific volumetric energy density of hydrogen, blending may not have a tangible decarbonising impact. Moreover, it can generate costs, problems in maintaining adequate methane number in the flow and difficulties in fuel uptake by vulnerable customers.[Interview 8] Blending seems to be more applicable in the specific gas grid cases or performed on-site at the consumer's site (example gas turbines). Overall, retrofitting national grid for hydrogen blending purpose in most of the cases might be unfeasible and dedicated hydrogen pipelines are seen by the experts as a future for hydrogen transport.[Interview 7,8]

The topic of hydrogen is crucial to the net-zero objectives of the European Union, however, there are many challenges to overcome before a full-scale market development can take place. While many ideas to support the development of the hydrogen market are being considered, none of them solve the problems of hydrogen deployment entirely. Despite challenges regarding hydrogen competitiveness, supply and origin, the market is finding solutions for its successful implementation into the economy. Information introduced and analysed in this chapter paint the picture of subnational level of governance regarding hydrogen development (EU strategy) and describe market conditions and barriers in which Polish national hydrogen market is to develop.

Chapter 2: Hydrogen policy and market conditions in Poland

This chapter includes an overview of the current state of energy and hydrogen market in Poland, focusing on the conditions that facilitate the development of a low-emission hydrogen market. The Polish Hydrogen Strategy is also analysed and compared with the guidelines of the European Hydrogen Strategy. The chapter concludes with a summary of the financing support schemes, which are currently available for the development of hydrogen in Poland. Based on the findings of the previous chapter and the current state of the market in Poland, the relevance of the current hydrogen policy and financing options are analysed.

Current Landscape of Renewable Energy Sources and Hydrogen Markets

Total greenhouse gas emissions in 2023 Poland decreased compared to 1990 by 18.3%, far lower than the overall total decrease in the EU at 32.5% (fig. 15). Power sector noted biggest emission decrease (48.5%), but it still remains the most emissive power sector in Europe with emissivity of 666 kgCO2 per MWh.[35] Fossil fuels are the main fuel source of the country's energy mix (fig. 17), with the high share of coal-based generation in the country. However, efforts are being made to continue and intensify actions towards decarbonisation of Polish energy system.

Wind and solar generation capacity, which corresponds to 40% of the countries installed capacity noted rapid growth. Especially, in the last two years when total yearly RES generation increased by 20% each year (fig. 16).[36] Due to that, the share of power generation corresponding to coal compared to 1990 decreased to around 60% in 2023, recording all-time low power utilisation rates.[35] Biggest RES generation corresponds to onshore wind, solar PV and the use of biomass. Poland is also looking to implement nuclear power in the energy mix, using both small modular reactors (SMR) and constructing nuclear power plants. Two new nuclear power plants are to amount to between 6-9 GW of non-emissive capacity in 2036.[37] Utilization of SMRs is also considered both by national and private companies for heat and power generation purposes.[38]

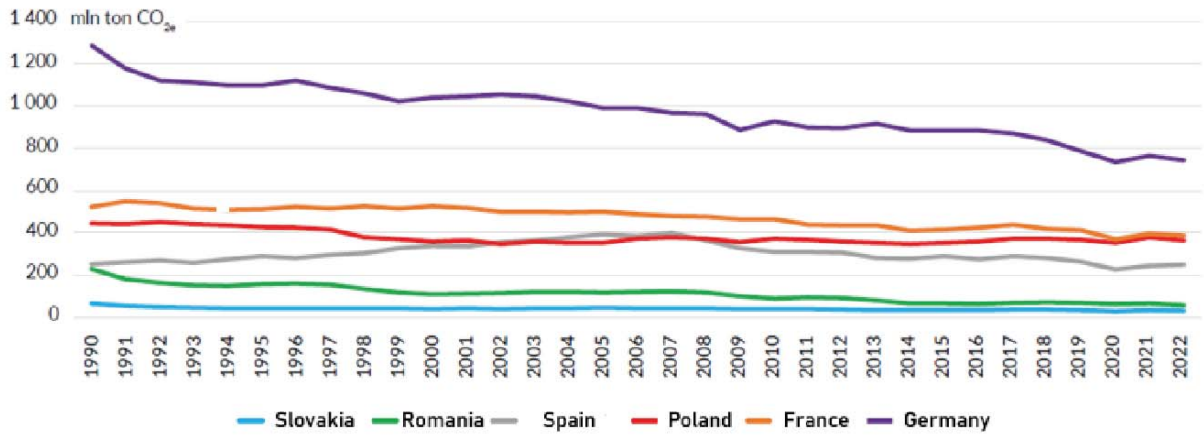

Figure 15: Change in greenhouse gas emissions, selected EU countries (2022). [35]

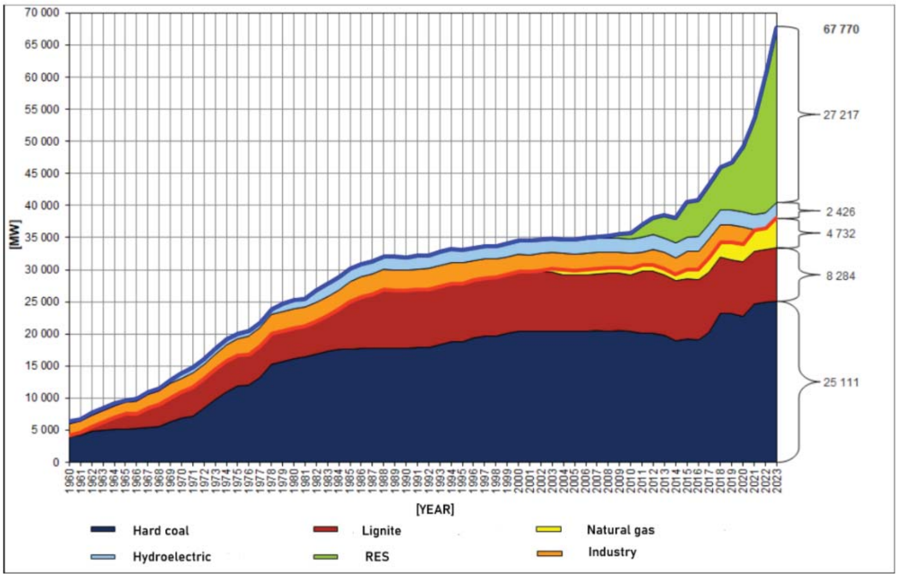

Figure 16: Growth rate of installed capacity in the NPS between 1960 and 2023. [36]

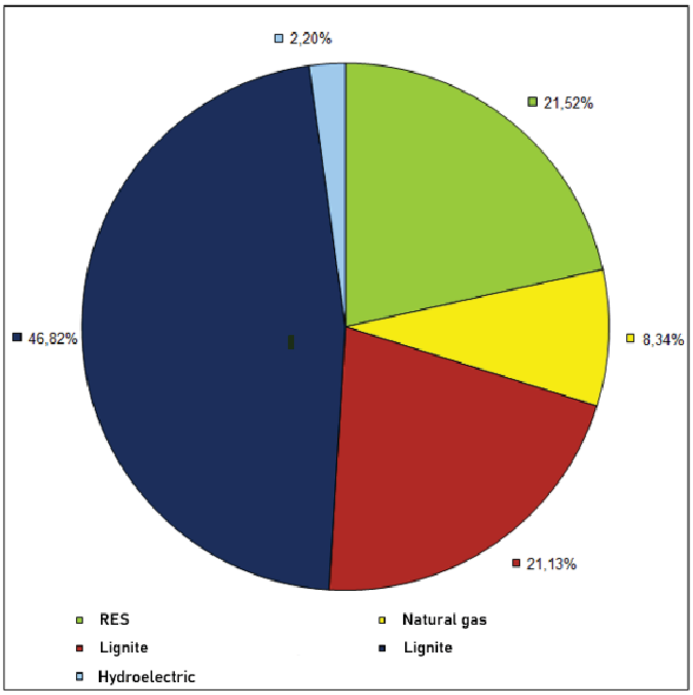

Figure 17: Share of national electricity production of power plants by type of fuel in 2023. [36]

Despite these new RES capacities, power generation remains the most carbon-intensive sector of the Polish economy. Other high-emitting sectors include transport, industry, agriculture heating sector and household fuel combustion (fig. 18). Decarbonisation of transport poses significant challenge as this is the only sector which noted an increase in emissions in 2022. Energy-intensive industries' emissions are presented in the figure 19. It should be borne in mind that, emissions corresponding to fuel combustion in the figure account for 44-72% of greenhouse gas emissions (depending on the sector), and the remaining emissions are the process emissions.[39] The high emissivity of the Polish economy will have a direct impact on Polish industry. The costs of carbon taxing mechanisms, such as the EU Emissions Trading System (ETS), will result in higher prices and worsened competitiveness on the international market.

With the introduction of ETS II, which will also impact the heat and transport sectors, the financial repercussions of maintaining a high-carbon economy will be significant for Poland. In light of this well-known fact, it is reasonable to inquire as to why the Polish economy is not being decarbonised at a more rapid pace.

One of the causes contributing to the moderate pace of emission reduction in Poland is the growth in energy demand. Over the years, the Polish economy has been developing, leading to an increased demand for power. Furthermore, ongoing trends of electrification of transport, heating and cooling have also contributed to this phenomenon. The number of electric cars, heat pumps and air conditioning units keep increasing (fig. 20). Unfortunately, in recent years, to meet the rising power demand, most of the newly installed conventional generation capacities have been fossil fuel based. The consequence of this approach was the occurrence of a peculiar incident. Despite the implementation of measures to reduce carbon emissions, namely the partial electrification of the transport and heating sectors, the desired result of significant decarbonisation has not been achieved. The new devices are powered mainly by coal-fired electricity.

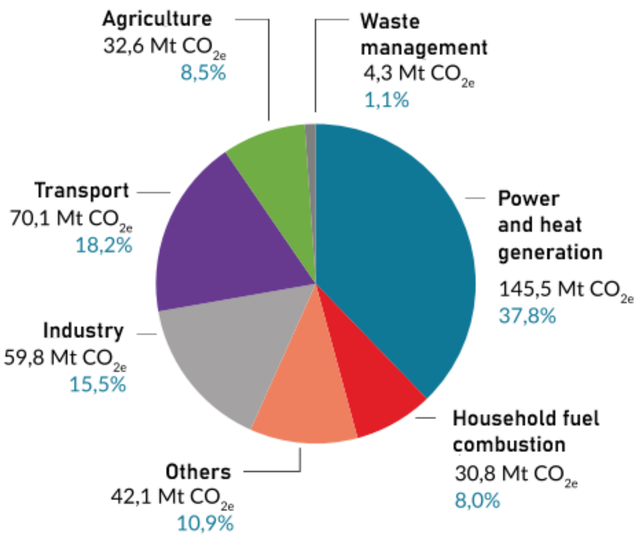

Figure 18: Structure of greenhouse gas emissions in Poland in 2022. [35]

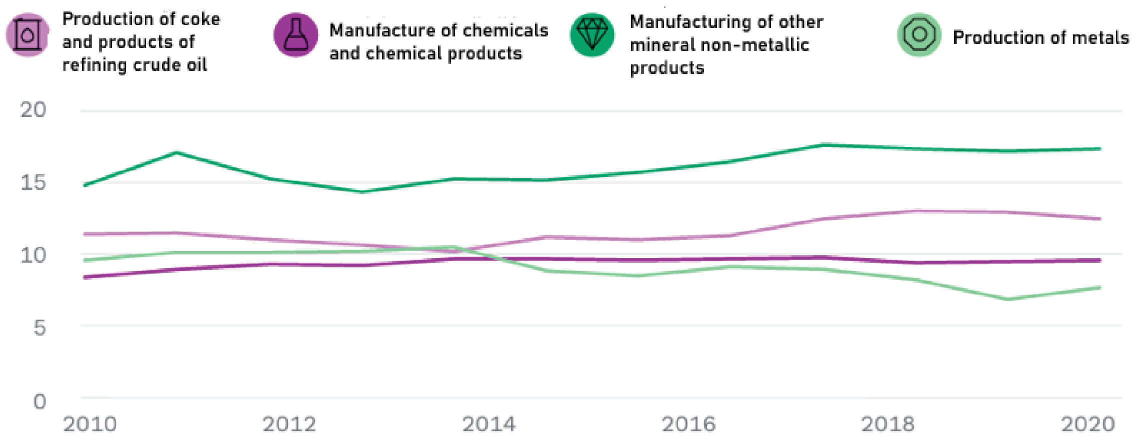

Figure 19: CO2 emissions from energy-intensive industries 2012-2022 (Mt CO2). [39]

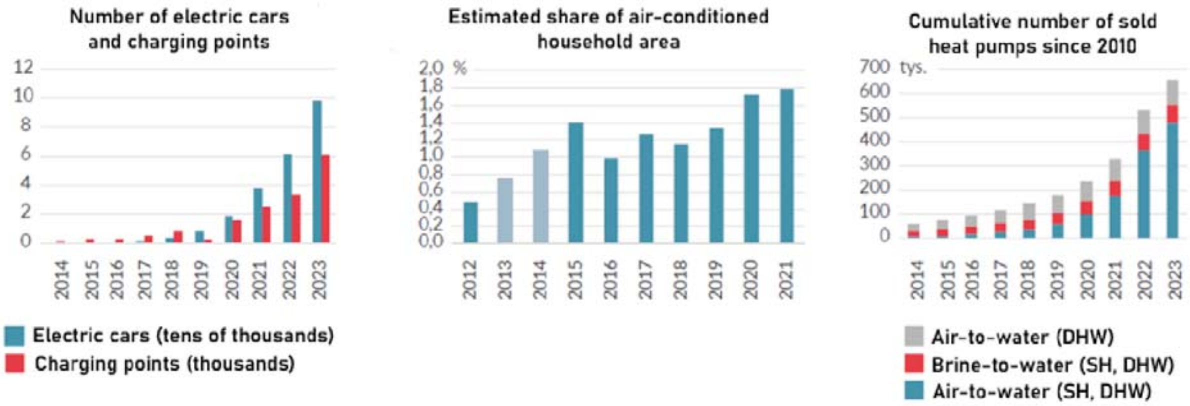

Figure 20: Factors increasing power demand. [35]

The most significant constraint on the pace of decarbonisation in Poland is the current state of Polish power transmission grids. The Polish national grid was designed based on the concept of a centralised energy system, with large power plants typically located near coal deposits, which are concentrated in the south of Poland. The lower costs of transporting and transmitting energy in this region have benefited industry and cities, prompting their development (fig. 21,22). The current transmission system was largely impacted by this phenomenon. Nowadays, it is not yet prepared to meet the challenges of the new energy system, which requires more flexible and modern electricity grids. The necessary investments to extend and improve transmission capacity to connect dispersed RES capacities with consumers have not been made on a sufficient scale to allow rapid and efficient introduction of RES into the energy mix. As a result, there is no cost-effective and straightforward way to connect areas with the most favourable conditions for RES generation with areas with high energy consumption. The current state of the transmission network gives rise to concerns regarding its stability, which may in turn result in transmission difficulties.[40] The condition of the transmission networks is suboptimal, with cable lines, overhead lines and equipment being outdated (fig. 23).

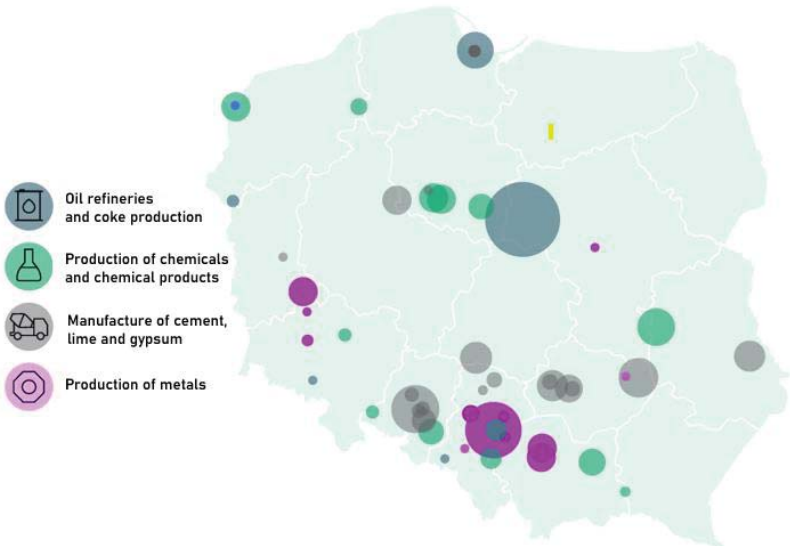

Figure 21: Largest CO2 emitters from industry. [39]

Figure 22: Polish high-voltage transmission grid. [41]

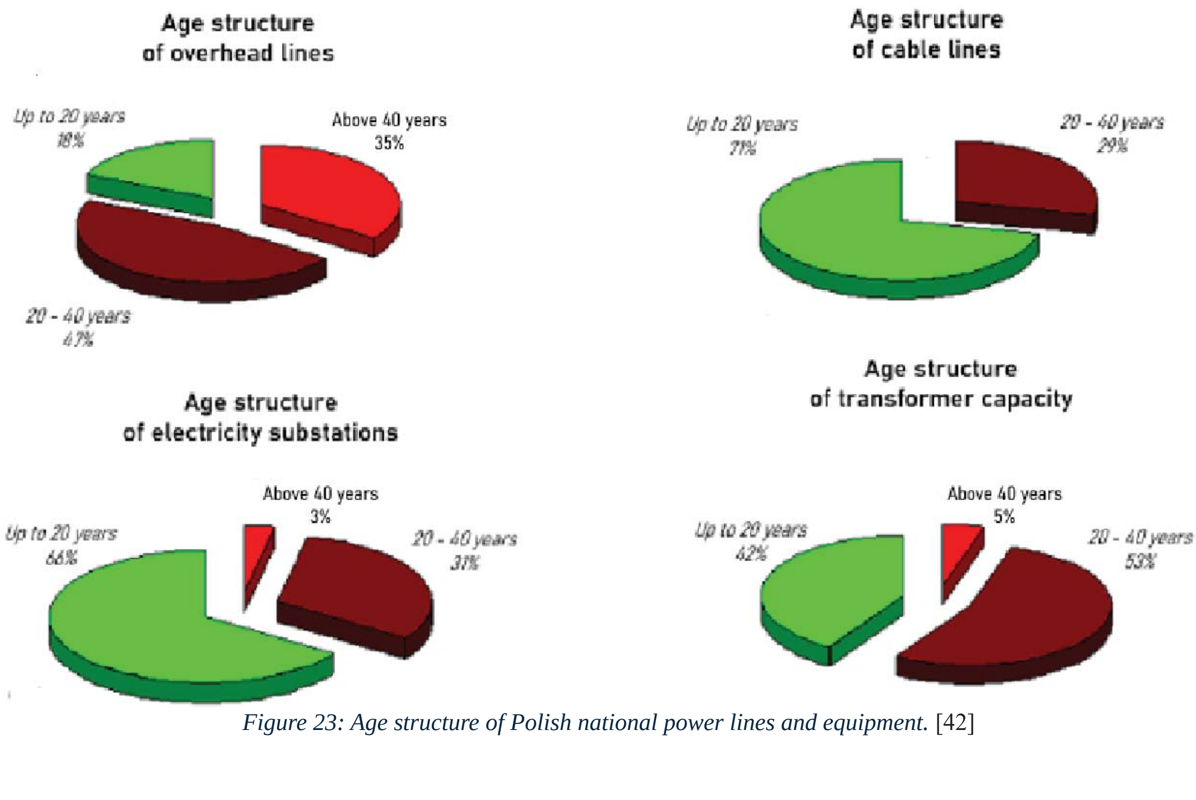

Figure 23: Age structure of Polish national power lines and equipment. [42]

State of the grid also restricts electrification processes, as new energy-intensive equipment requires the grid, able to handle large new connection capacities.[43] Moreover, as the number of RES installations increases, the problems associated with the transmission network also intensify. The volume of renewable energy, lost due to curtailment, increased from 8.4 GWh in 2022 to approximately 74.4 GWh in 2023.[35] Total RES capacity, which didn't acquire building permits due to lack of conditions for connection by the electricity grid, amounted to 51GW in 2022.[44] A Polish economy seeking to decarbonise cannot afford to sustain such losses. In order to facilitate the decarbonisation of the Polish energy system, it is necessary to implement wide-ranging actions. It is evident that investment in the energy transmission grid is a crucial factor in facilitating the integration of new renewable generation capacity, as well as the implementation of energy storage solutions. Another indication of the necessity for energy storage within the national power system (NPS) is the utilisation of the only noteworthy energy storage facilities currently in operation – hydroelectric pumped storage power plants. In 2023, the generation of these facilities reached 1.4 TWh, representing a record utilisation, 22% higher than in 2022. This claim can also be supported by the big increase in natural gas power plants generation in 2022 (+41%) which are characterised by higher flexibility and respond faster to RES fluctuations.[35]

The need for energy storage in Poland, especially large-scale, long-term storage, is particularly evident when comparing the days with the lowest and highest generation in the power system in 2023. The power demand curves on 11 June 2023 (fig. 24) and 28 November (fig. 25) show how significantly the situation of the Polish power system changes during the year.

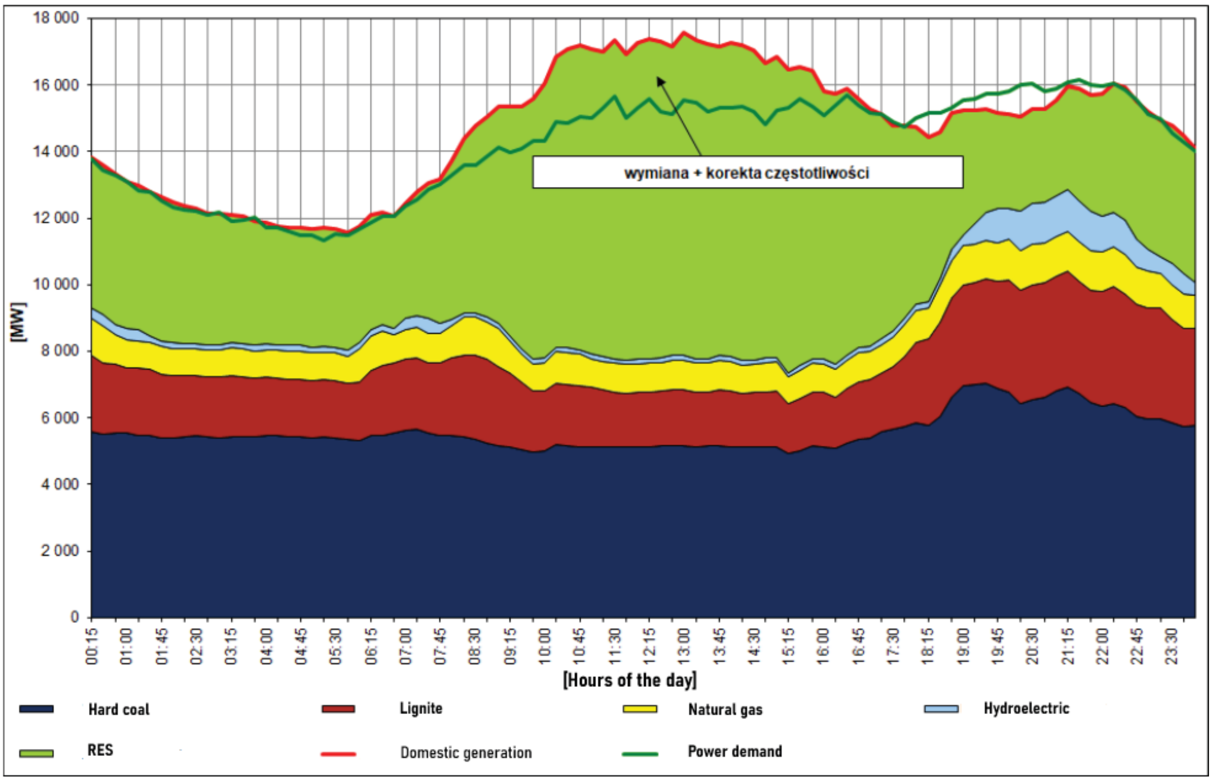

Figure 24: The trajectory of power demand in the NPS on the day on 11th of June 2023. [36]

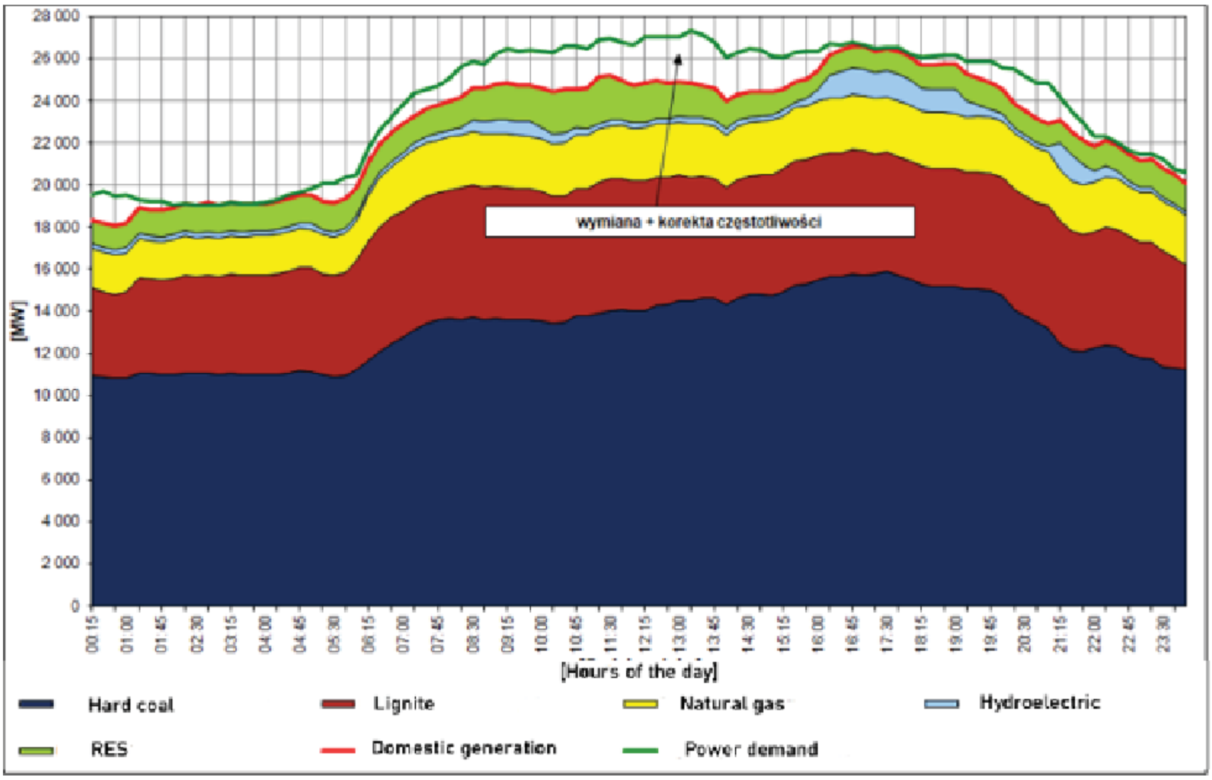

Figure 25: The trajectory of power demand in the NPS on the day on 28th of November 2023. [36]

On the 11th of June, due to favourable wind conditions and high solar irradiance, RES generation accounted for more than 50% of electricity consumption for part of the day. The amount of electricity generated on the market was so high that for the first time in history, Poland experienced negative prices on the intraday market. This means that operators of conventional energy sources were willing to pay for generation rather than incur the costs associated with reduction of the load. Electricity was sold through international connections. The conventional power sources were kept at low capacity to ensure their operation. They had to operate as RES generation dropped off around 19:00. Fossil fuel and hydro (including pumped storage) power generation had to be increased quickly and electricity was bought from abroad to keep the system stable.

On 28th of November RES were responsible for less than 10% of supplied power. Weather conditions were unfavourable, temperature low, the sun during that period sets earlier. It resulted in higher electricity demand for heating and lighting. Due to all of those factors, almost all of the power was fossil fuel based, even if RES corresponded to 40% of the national energy mix capacity.

The presented changes in power demand and sources utilised to supply it during these two days show that the Polish energy system would benefit from energy storage and generation sources allowing for rapid load switching. [45] Both on a daily and seasonal basis, energy storage would allow for smaller number of conventional power plants needed as a capacity reserve and therefore reduce costs and emissions. Using hydrogen for this purpose is a solution worth considering, especially as it is also used in other sectors of the economy.

Currently almost all hydrogen produced in Poland is grey. It is mainly obtained using steam methane reforming process or as a by-product of other production processes (table 4). The main hydrogen production market players include Grupa Azoty Puławy and Orlen (owner of the Lotos Group). Yearly production varies due to the prices of natural gas, which is the most cost intensive variable of grey hydrogen production. Hydrogen in Poland is mainly produced for refinery operation, fertiliser and chemical production or as a by-product of other processes (fig. 26). Large production units are mostly located in southern Poland, with a few in central Poland and individual plants in the north (fig 27). Hydrogen is consumed directly at the production site, and there are no interconnections between the facilities.

The demand for hydrogen in Poland is high and customers will need it no matter of the emissions associated with production process.[Interview 4] Even if new sectors such as transport or heating would not adopt hydrogen solutions, investment in low-emission hydrogen is needed to decarbonise the grey hydrogen currently used in industry.

Table 4: Grey hydrogen production in Poland by biggest market participants in 2022. [46]

Name	**Type of process**	**Production capacity [t/y]**	**Production [t/y]**
ORLEN	Steam reforming - Refining sector	232836	190926
Gdańsk Grupa Lotos	Steam reforming - Refining sector	168809	138423
Puławy Zakłady Azotowe	Steam reforming - ammonia	214620	133536
Police Zakłady Chemiczne	Steam reforming - ammonia	105120	65405
Włocławek Anwil S.A. (Grupa Orlen)	Steam reforming - ammonia	92327	57446
Jedlicze ORLEN	Steam reforming - Refining sector	58205	47728
Kędzierzyn Zakłady Azotowe 2	Steam reforming - ammonia	70844	44079
Kędzierzyn Zakłady Azotowe 1	Steam reforming - ammonia	68180	42421
Tarnów Zakłady Azotowe	Steam reforming - ammonia	50602	31485
ORLEN	By-product - Ethylene	11957	9804
Tarnów Zakłady Azotowe	Steam reforming - Chemical sector	6237	4865
Włocławek Anwil S.A. (Grupa Orlen)	By-product - Chlor-alkali	5460	3767
Zakłady Chemiczne/PCC Rokita	By-product - Chlor-alkali	5208	3594
Puławy Zakłady Azotowe	Steam reforming	3898	3041
Bochnia Stalprodukt	Steam reforming	3767	2938

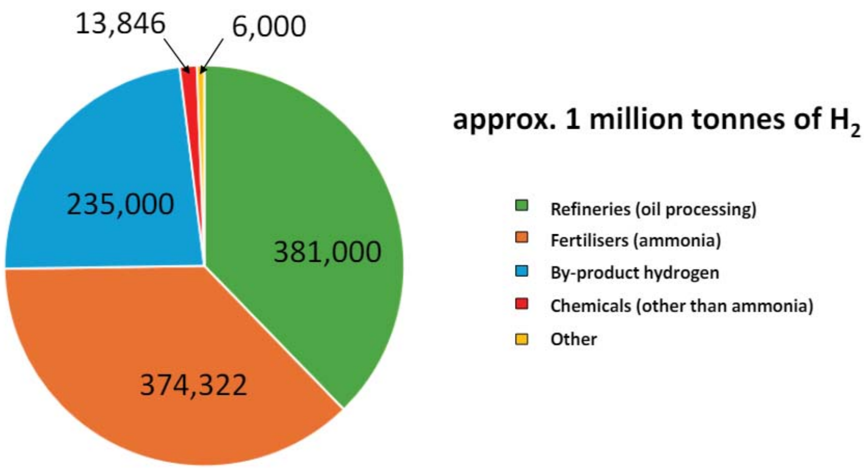

Figure 26: Hydrogen production in Poland including the consumption sector in 2022. [47]

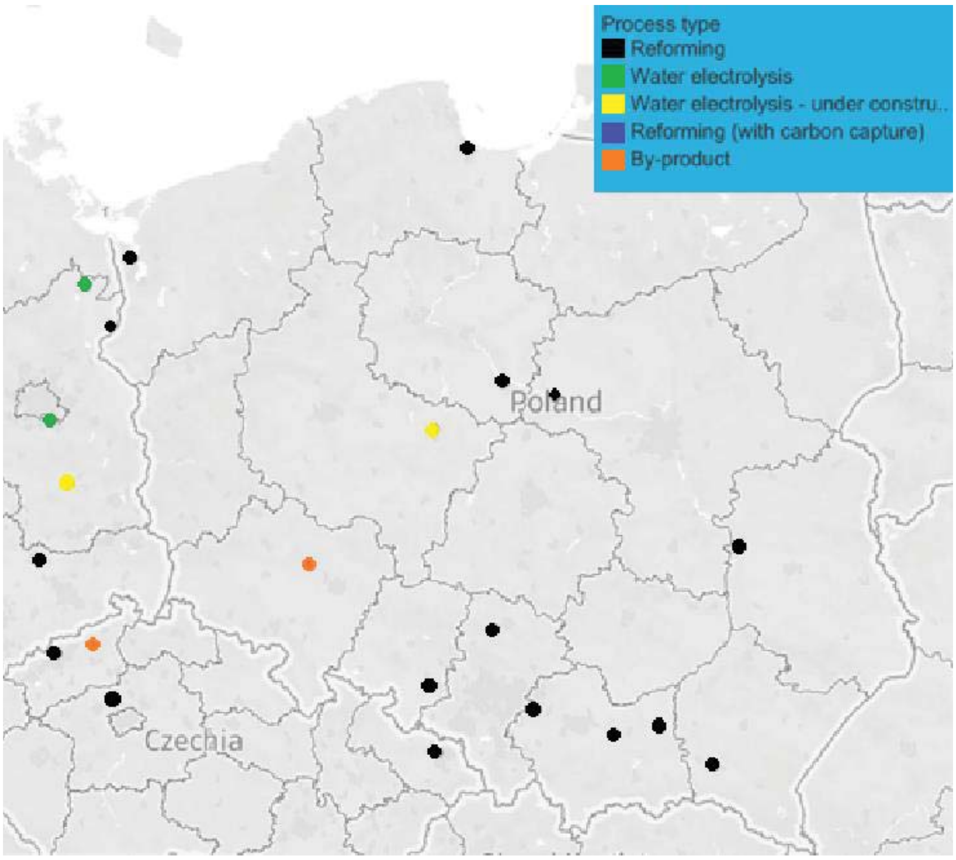

Figure 27: Largest hydrogen production facilities in Poland in 2022.[46]

Strategic Alignment: Poland's Hydrogen Strategy in EU Context

Knowing the current state of hydrogen market in Poland, we can analyse Polish Hydrogen Strategy in light of the European Hydrogen Strategy. The comparative analysis of the Polish Hydrogen Strategy refers to the EU Hydrogen Strategy without considering the new objectives introduced by REPowerEU in 2023, mentioned in chapter 1. The Polish Hydrogen Strategy was introduced in 2021 and was developed based on the EU Hydrogen Strategy as presented in 2020. It is worth mentioning that the Polish Hydrogen Strategy is in the process of being updated and the new targets will most likely take into account the new REPower EU amendments.

Polish Hydrogen Strategy aims to develop Polish low-emission hydrogen market within the country, which will bring together technologies of hydrogen production, storage distribution and utilisation and connect it with different sectors of Polish economy. Strategy was based on the up-to-date analysis of hydrogen market in the country and hydrogen value chain. It outlines the way forward for the national hydrogen market development over the periods up to 2025 and 2030, based on progressive targets. Overall, strategy suggests that, initially, specific case studies and feasibility analyses should be conducted, alongside research efforts to ensure the cost-effectiveness of applied hydrogen technologies Later, based on the lessons learnt, pilot projects and scale up programs are to be commissioned. The strategy emphasizes the importance of hydrogen storage technologies for advancing renewable energy sources (RES) while avoiding strain on the national grid in light of ongoing electrification of the transport and heating sectors and increase in power demand. Strategy also promotes use of hydrogen in different energy-intensive sectors of the economy as a decarbonisation accelerator.

With regard to hydrogen production capacities in Poland strategy sets targets for low-emission hydrogen rather than renewable one. It is most likely due to large variety of hydrogen production methods which are being considered. Among others electrolysis, biomass, biogas, biomethane usage as well as waste and waste gas utilisation. Also, blue and in the future pink hydrogen is considered. Not all of those technologies meet renewable hydrogen emissions standards, and it is understandable that if Poland aims to exploit its potential for hydrogen production from all those different sources, it ties the future with low-emission hydrogen rather than renewable one. Lack of the concrete hydrogen production target should be pointed out. Many hydrogen production facilities can be commissioned but, in the end, the amount of hydrogen produced will drive forward hydrogen market development.

The strategy's objectives focus on the use of hydrogen in four sectors of the national economy – industry, transport, power generation and heating. In the power and heating sectors, most projects are expected to be based on research and development by 2025. By 2030, co- and poly-generation plants such as CHPs, large scale hydrogen energy storage and hydrogen fuel cells systems should be implemented. Hydrogen is seen as one of the solutions to decarbonisation of district heating systems. In industry, low-emission hydrogen is to replace the grey hydrogen, currently used in the chemical, petrochemical, refinery sectors and later introduced to energy-intensive sectors. To achieve this, pilot projects are to be carried out and plans put in place, to procure the necessary hydrogen supply. The operation of hydrogen valleys and the connection of Polish industrial facilities to the common European hydrogen infrastructure is to support this process by 2030. The transport sector is extensively covered in the Polish strategy, although, not as strongly emphasis is placed on it in the European strategy. Hydrogen technologies are to be implemented in public transport, heavy-duty road transport and long-distance transport. This includes road, rail, sea, and river transport as well as aviation. There are very clear targets for the number of refuelling stations (32) and the number of hydrogen buses (100-250) in operation by 2025 and even more ambitiously 800 to 1000 buses by 2030. In other transport sub-sectors, research and pilot projects are to be developed by 2025, with the vision to introduce hydrogen-powered solutions in other transport modes by 2030. The Polish Hydrogen Strategy also provides guidelines for the development of hydrogen transmission systems by pipelines, road, sea, and rail. The current gas transmission network is to be analysed for hydrogen blending and new dedicated hydrogen pipelines should be introduced. A broad extent of technologies is to be considered to enable the storage of hydrogen above and below ground. In addition, the strategy identifies the legislative changes necessary to introduce hydrogen technology into the Polish economy. The measures in the strategy consider the bigger picture of the specific conditions of the Polish market and outline actions in a wide range of areas. Overall, this analysis supports the claim that Polish Hydrogen Strategy follows EU's strategy guidelines. Nowadays, emphasis should be placed on its implementation.[Interview 8]

The table below outlines and compares the main objectives of the European Union Hydrogen Strategy and the targets of the Polish Hydrogen Strategy in the short and medium term.

Table 5: EU and Polish Hydrogen Strategies compared.

A Hydrogen Strategy for a Climate-neutral Europe	Polish National Hydrogen Strategy strategy until 2030 with an outlook until 2040	Comments on the Polish Hydrogen Strategy
Short term targets - up to 2024 for EU H2 Strategy, up to 2025 for PL H2 Strategy		
6GW of electrolysis capacity, production of 1 million tonnes of renewable hydrogen in the EU.	Commissioning of a low-carbon hydrogen production facilities with a capacity of min. 50 MW.	Lack of target for hydrogen production.
Reduce and replace industrial use of grey hydrogen in industry (refineries, steel making, production of ammonia etc.).	Creation of hydrogen deployment strategy and working towards the acquisition and application of low-carbon hydrogen for petrochemical, chemical and fertiliser production processes. Introduction of pilot projects.	No clear target for grey h2 reduction.
Adoption of hydrogen in transport where electrification is more difficult – local hydrogen city buses, commercial fleets etc.	Investigation feasibility and cost-effectiveness of the use of synthetic fuels in transport. Launch pilot programmes involving the use of hydrogen and its derivatives in public transport, heavy road, rail, sea, river and air transport and intermodal transport. Launch of hydrogen-powered zero-emission buses - 100 to 250 hydrogen buses.	Clear target, wide perspective in terms of applications.
Deployment of hydrogen refuelling infrastructure.	Development of a network of hydrogen refuelling and bunkering stations, min. 32 new stations. Focusing on infrastructure development in agglomerations and densely populated areas and considering the trans-European transport network corridors.	Clear target, specification of the desired investment location.
Usage of hydrogen fuel-cell trains where it is viable.	Development of hydrogen trains/locomotives to replace their fossil fuelled counterparts on routes not foreseen for electrification.	The objective specifies in which cases hydrogen should be implemented in rail transport.
Adoption of hydrogen inland, waterways and short-sea shipping.	Design work on the first vessels with a hydrogen-based propulsion system (e.g. ammonia, methanol). Hydrogen-powered vessels could provide a back-up for the planned Polish wind farms in the Baltic Sea and offshore coastal transport.	Good identification of where hydrogen deployment will be most effective.
Implementation of hydrogen technologies in aviation sector.	Introduce ammonia and synthetic fuels created with the use of hydrogen in aviation, enabling its decarbonisation in the long term.	Lack of clear target.
Hydrogen usage for provision of heat for residential and commercial buildings.	R&D support for the development of poly-generation systems for residential blocks, office buildings, small estates and public buildings from 10 kW to 250 kW using fuel cells	Very specific objective in terms of technology, very general in terms of implementation.
Scale up of manufacturing of electrolysers capacity (up to 100MW).	R&D of low-carbon hydrogen generation technologies. Commissioning of hydrogen production facilities from low-carbon sources, processes and technologies with a total capacity of min. 50 MW.	Included not only electrolysis systems but also other methods of producing renewable hydrogen production together with blue and pink hydrogen production.

Plan of medium range backbone transmission infrastructure.	Development of hydrogen transmission and distribution networks. Preparation of an analysis of the most optimal form of energy transmission for the development of the hydrogen economy (transmission of electricity to electrolysis installations, transmission of hydrogen or SNG via existing infrastructure or transmission via dedicated pipelines. "Hydrogen Highway" - feasibility study of a dedicated hydrogen north-south pipeline.	The strategy states that for the current state, it is possible to blend 5% hydrogen into the gas transmission network.
Planning of carbon capture infrastructure and storage.	Identifying the preparation of carbon storage sites as a key issue.	No initiative for action in this direction.
Support of related skills development and labour market adjustments where needed.	Development of competencies and human resources to prepare qualified human resources for the development, construction and operation of hydrogen facilities (with emphasis on retraining workers from coal-dependent areas).	General target.
Policy towards functioning of international hydrogen market.	Standards of installation, produced hydrogen and transmission system according to EU standards.	Lack of clear target.
Hydrogen as a mean for daily and seasonal storage.	Consideration of hydrogen storage possibilities in above-ground and underground storage, support R&D in this area. Potential sites for storage: depleted oil and gas fields, aquifers, rock caverns, abandoned mines, salt chambers. Identify the need for the development of large above-ground buffer tanks in the longer term.	Large range of underground technologies considered, but it is very unmature technology. No objective for the development of aboveground storage activities.
Implementation of supportive policy framework to enable renewable and low-carbon hydrogen to contribute to decarbonisation at the lowest possible cost (considering industrial competitiveness and value chain implications).	Creating a regulatory framework for the functioning of hydrogen as an alternative fuel in transport. Development of a legislative hydrogen package, laying the foundations for the functioning of the market. Development of a legislative hydrogen package - legislation setting out the details for the operation of the market, implementing EU law in this area and introducing an incentive scheme for the generation of low-carbon hydrogen.	Precise objective in terms of the activities carried out and the timeframe.
Medium term targets up to 2030		
40 GW of electrolysis, 10 million tonnes of renewable hydrogen produced in the EU.	Aim for 2 GW of capacity for hydrogen production and hydrogen derivatives from low carbon sources, processes and technologies, including in particular electrolyser plants.	Target concerns low-emission hydrogen. Renewable hydrogen target not specified.
Hydrogen as an intrinsic part on integrated energy system.	Hydrogen as a way to support effective cooperation between the operation of the gas system and the electricity system in line with the concept of sector coupling.	Correct interpretation of the EU objective.
Renewable hydrogen competitive with other	Identification that the origin of hydrogen determines its competitiveness and that the price of RES electricity should oscillate	Identification of the main barrier to the

forms of hydrogen production.	between 10-20 EUR/MWh to enable hydrogen to be competitive in Poland.	implementation of the EU objective.
More, new applications of hydrogen in transport.	Start of operation of 800 to 1000 hydrogen buses, partially produced in Poland.	Good continuation of the target concerning hydrogen vehicles, lack of continuation of the target regarding new refuelling infrastructure.
Demand side policies to implement hydrogen to industry and transport sector.	Alignment of the legislation with the next revision of the RED hydrogen directive. Hydrogen is part of the Strategy for Responsible Development until 2020 (with an outlook until 2030), the Energy Policy of Poland until 2040 and the National Energy and Climate Plan.	Target met due to EU policies, not national initiatives.
Hydrogen has a role in balancing of electricity system.	Identification of opportunities to use electrolysis to as a possible solution to balancing the variability and discontinuity of renewable energy systems.	Lack of clear target.
Hydrogen used in daily and seasonal storage.	Start of the use of hydrogen as an energy carrier used for energy storage processes.	Lack of clear target.
CCS used in facilities which are nowadays producing grey h2.	Confirmation of the potential use of CCS systems as an interim solution in industry.	Lack of clear target.
Development of hydrogen valleys.	Establishment of at least 5 hydrogen valleys as centres of excellence for the implementation of the hydrogen economy, the integration of transport and industry sectors and the construction of the necessary infrastructure.	Clear target, realized however a different definition of the hydrogen valley is used.
Hydrogen heat used in commercial and residential buildings.	Commissioning of co- and poly-generation facilities, e.g. combined heat and power plants of up to 50 MW and the use of fuel cells from 10 kW to 250 kW. with the use of hydrogen to produce heat for blocks of flats, office buildings, small housing estates and public facilities.	Very specific objective in terms of technology, very general in terms of implementation.
Emergence of EU-wide transmission infrastructure.	Further development of hydrogen refuelling and bunkering infrastructure. Adapting the gas network to be doped with 10% of the gas mixture other than natural gas. Introducing SNG produced in P2G systems into the gas network.	The technical condition of most of the Polish gas pipelines does not allow for feasible hydrogen blending.
Competitive hydrogen market with cross border trade.	Integration of the emerged investments into a common European infrastructure. Supply of finished hydrogen and hydrogen technology products to the market for domestic and foreign players.	Correct interpretation of the EU objective.

Based on the analysis in the Table 3, it can be said that Polish Hydrogen Strategy implements actions which are in line with European Union Hydrogen Strategy. Each of the identified objective of the European document finds a corresponding target within the national strategy. Yet, Polish Hydrogen Strategy is being updated[48] and there are some compelling reasons behind this.

The first criticism of the Polish Hydrogen Strategy is that it fails to consider why hydrogen is being developed in Europe.[Interview 8] The most important function of the hydrogen economy is to be part of the decarbonisation efforts. National hydrogen strategy should be designed based on, not only European Union Hydrogen Strategy, but also on the dedicated national decarbonisation roadmap.[Interview 1] The absence of such a roadmap and the failure to consider the importance of decarbonisation in the creation of a national hydrogen market will result in limited long-term results, even for well-designed components of the hydrogen strategy.[Interview 8] There is a need for implementation of operational hydrogen strategy which would focus not only on setting targets related to hydrogen but rather on designating who is responsible for fulfilment of the set objectives.[Interview 9] Leaving the development of individual decarbonisation strategies to industrial players, and only directing them towards hydrogen technologies may not produce tangible results in terms of both decarbonisation and hydrogen market development. Those actions should be coordinated at national level in light of a deliberate national decarbonisation strategy.[Interview 8]

Another concern is the uncertainty about timeframe in which strategy objectives should be implemented as well as their scope. Some assumptions adopted by the strategy are said to be unrealistic[Interview 8], especially in the light of ongoing delays of hydrogen projects and cases of hydrogen investments being abandoned due to too long payback period.[Interview 10] One interesting suggestion for improving the shape of the strategy, would be to distinguish between two hydrogen markets. The first is the current grey hydrogen market, which needs to be decarbonised, and the future hydrogen market in sectors where hydrogen is being introduced.[Interview 8] Dividing the hydrogen market in this way would allow for separately addressing challenges such as prioritizing the use of low-carbon hydrogen in long-term strategic industries and forecasting the demand for hydrogen in new sectors.

The strategy also neglects to consider the importance of direct involvement of regional development strategies in hydrogen market development. Such initiatives have the potential to maximise benefits through know-how of the region's local resources and opportunities, and would allow for the anticipation of risks and critical points for hydrogen development in a particular region.[Interview 1] It can be assumed that the contribution of the regional authorities to the development of the hydrogen market was foreseen by their participation in the hydrogen valleys activities. However, there is no indication to support this claim other than an ongoing presence of regional authorities in hydrogen valleys.

There are also widespread comments indicating a lack of sufficient, broader support for the hydrogen market development beyond the strategy document itself. This relates to legislation[Interview 6,7,10], hydrogen transmission infrastructure[Interview 7,9] or financial support mechanisms scope[Interview 1,9,10]. This indicates that even though Polish Hydrogen Strategy follows well the guidance of the European Union Hydrogen Strategy, more coherent and coordinated actions are necessary to ensure efficient implementation of hydrogen market in Poland.

Financial Support Available for Low-emission Hydrogen Market Development

Given the ambitious targets set by the EU and Polish Hydrogen Strategy and the high costs associated with hydrogen projects, EU and national financial support schemes are available for the development of the hydrogen market in Poland.

European funds cover a wide range of projects. Part of the funds focus on innovation and research, helping development of new hydrogen technologies and fostering first pilot applications implementation.[Interview 5] As some of the parts of hydrogen economy are well-developed [Interview 7] support is also available for commercialisation and scale up of hydrogen technology. EU funds can be used for implementation of new low-emission hydrogen production capacities, development of hydrogen infrastructure (new pipelines and retrofitting of natural gas pipelines, refuelling stations) and utilisation in power and heat generation as well as industrial applications.

Table 6: EU funds and programmes enabling the financing of hydrogen related projects. [49]

Project	Hydrogen eligible funding	Hydrogen projects	Comments
Connecting Europe Facility (CEF) – Energy & Transport	CEF Energy – €5.84 billion, CEF Transport – €21.1 billion	International hydrogen infrastructure (transmission and distribution) with connected storage facilities, focusing on missing cross-border links. Development of electrolysers, Refuelling infrastructure (road and rail transport, maritime and inland ports and waterways). Smart low-carbon gas grids equipment development	Accessible for projects listed on EU's Projects of Common Interest (PCI) and Projects of Mutual Interest (PMI). Both for new hydrogen pipelines and retrofitting natural gas pipelines for the hydrogen purposes. Eligible only electrolysers +100MW. Actions focused along Core Network, and on the Comprehensive Network (TEN-T).
European Regional Development (ERDF) Fund, Cohesion Fund (CF) and REACT-EU	ERDF – €234 billion, CF – €234 billion, REACT–EU – €50.6 billion	ERDF – hydrogen projects which support entrepreneur projects in the EU, towards decarbonisation of the economy. CF – primarily for environmental and transport investments. REACT-EU – support economy recovery mechanisms and crisis repair	Hydrogen projects are not mentioned in key targets of the funds, therefore there need to be evaluated if they their scope meets objectives of the program. Part of the funds included in "Funding" column are being redistributed to other funds (like CEF).
Horizon Europe	Pillar II – €53.5 billion, Pillar III – €10 billion	Hydrogen research and innovation projects (pilot, testing, demonstration and development) in academic, market and industrial environment.	Projects related to science excellence, EU industrial competitiveness and innovation. Pillars II and II include hydrogen and aim for deployment of low carbon industry with focus on

			research and breakthrough technologies.
Innovation Fund	Depending on the carbon price – equivalent of 450 million EU ETS allowances (€20 billion at carbon price €40 t/CO2)	Hydrogen projects related to substitution carbon-intensive technologies, RES, energy storage, CCS, electrolysers manufacturing and utilisation of hydrogen in different sectors.	Commercialisation of innovative low-carbon technologies in through incentives. High flexibility in terms of hydrogen projects support – both hydrogen production and utilisation, large and small scale projects.
Invest EU	Expected €372 billion to provide guarantees for projects by public and private investment	Investments in low-carbon gas production, commercial scale supply and on-site storage in energy sector. Development of transport modes (refuelling stations, blending etc.)	Mostly targeted strongly economically feasible projects with some exceptions. Different projects support type possible, depending on project life cycle.
Just Transition Fund (JTF)	€19.2 billion	Hydrogen mobility projects – vehicles and refuelling stations, R&D of hydrogen technologies and hydrogen hubs.	JFT focuses on regions affected by energy transition. Targeted support only for projects alleviating socio-economic costs of transition and implement Territorial Just Transition Plans.
LIFE programme	€1.94 billion	Hydrogen strategic and technical programs in line with program objectives.	Objectives - establishing the policy framework at different level of governance fostering a shift to clean energy, adoption of new technology, digitalization, development of local investments and skills.
Modernisation Fund	Depending on the carbon price – equivalent of 2% of EU ETS allowances for (€25 billion at carbon price €40 t/CO2)	Hydrogen production and utilisation projects, energy efficiency improvement projects with hydrogen involved, energy storage and modernisation of energy networks.	Decision of the form of the support lies in competences of the given country. Poland is third biggest beneficiary.
Recovery and Resilience Facility (RRF)	€337.97 billion in grants and €385.85 billion in loans	Demonstration and first development of hydrogen projects, both production and utilisation of hydrogen in transport.	Funds distributed along national recovery and resilience plan is approved by the EU Council.

Total investment volumes of the funds are substantial, hover they are devoted to specific objectives which can be met in the different ways. Funds analysed (table 6), have specific grading criteria and budget to be spent between 2021-2027. Not all the funding is granted to hydrogen projects, as they have to compete with other projects relevant to funds targets. Hydrogen projects are in the challenging position, facing this competition. They are more expensive as the hydrogen market didn't mature enough yet to overcome current hydrogen technology problems (described in chapter 1).

Funding is distributed through projects across all of the EU, which means that countries with better conditions for hydrogen production, have a clear advantage in terms of financial criteria. Some of the funds have very specific requirements that exclude part of the hydrogen projects from consideration. The hydrogen market is expected by the EU to play a significant role in achieving net-zero emissions by 2050, but the support schemes available for hydrogen do not reflect these ambitious goals. More programmes dedicated only to hydrogen are needed, which would allow for proper market formation.

One of the initiatives set to target hydrogen projects specifically is the European Hydrogen Bank (EHB), which is in part financed via the EU Innovation Fund. The first auction was held on 23 November 2023. Its objective was to increase the production capacity of renewable hydrogen (RFNBO). Producers from Europe submitted bids during the auction for an additional premium per kg of hydrogen produced, with the aim of covering the price difference between production costs and the market price of hydrogen. In order to be eligible for funding, projects had to meet specific technological criteria. These included a minimum electrolyser capacity of 5 MW, the status of RFNBO for hydrogen throughout the duration of the programme, and the provision of guarantees in terms of experience and financial capabilities. Only projects that had not yet started construction were eligible to take part in the auction. Cumulation of different support funds was acceptable as long as it was related to different, identifiable eligible costs, i.e. cumulation was not allowed for partially or fully overlapping costs. Projects could apply for fixed premium of 4,5 EUR, granted for 10 years, and must start operation within 5 years from receiving subsidy grant.

The first auction received 132 applications from which 7 projects were selected. The premium requested by winning projects ranged between 0.37-0.48 EUR. Total €720 million was awarded by grants of between €8 million and €245 million. Average levelized costs of hydrogen production by auction participants ranged between 5.8-13.5 EUR/kg.[50] It is no surprise, that two Polish projects which took part in the auction were not selected, as the winning projects are located in countries with low-cost renewable energy generation (Spain, Portugal, Finland, and Norway). Even so, the low price of the winning bids came as a surprise. The difference between the costs of hydrogen production and market price of hydrogen in those countries is large (even with the extra premium gained).[Interview 9] It is too early to assess the impact of European Hydrogen Bank auction [Interview 1] and the detailed analysis of the influence of the auction on the hydrogen market development can be performed after the commissioning and operation of new electrolyser capacities. Importantly, if all projects proceed as assumed, their combined hydrogen production will only reach 1.6% of the EU's total 2030 hydrogen production target. It can be expected that future winning bids in the next EHB auctions will be higher, with cheaper projects securing funding and less feasible projects beginning to receive the support.

Table 7: Winning projects of first auction of European Hydrogen Bank. [51]

Project	Coordinator	Country	Bid volume (kt_H2/ 10 yrs)	Bid capacity (MWe – Mega watts electric)	Expected GHG avoidance (kt_CO2/ 10 yrs)	Bid price (EUR/ kg)
eNRG Lahti	Nordic Ren-Gas Oy	Finland	122	90	836	0.37
El Alamillo H2	Benbros Energy S.L.	Spain	65	60	443	0.38
Grey2Green-II	Petrogal S.A.	Portugal	216	200	1477	0.39
HYSENCIA	Angus	Spain	17	35	115	0.48
SKIGA	Skiga	Norway	169	117	1159	0.48
Catalina	Renato Ptx Holdco	Spain	480	500	3284	0.48
MP2X	Madoquapower 2x	Portugal	511	500	3494	0.48

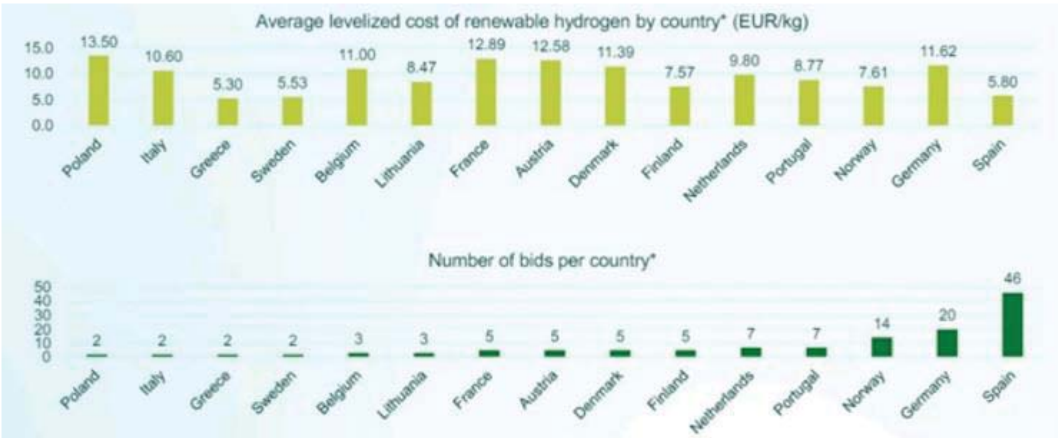

Figure 28: Summary of the first auction of European Hydrogen Bank. [50]

European Hydrogen Bank was the good initiative directly supporting the increase of hydrogen generation capacity in the EU, even if it does not fully match the scope of EU Hydrogen Strategy targets. This auction and new editions in the future will help to increase hydrogen production in Europe however, the impact of European Hydrogen Bank might not be seen in Poland for a while. Cost of hydrogen, presented by the Polish projects, was the highest in Europe.

Interviewed experts point out that more initiatives supporting hydrogen market development are needed. Especially in industrial applications[Interview 6, 9], for scale up of hydrogen vehicles manufacturing[Interview 6] as well as pilot projects and commercialisation [Interview 1]. For hydrogen market to develop efficiently, all areas of hydrogen economy should be supported, allowing for a market to form and facilitate price reduction of hydrogen technologies. Support schemes in Poland were classified as inadequate to meet the challenges of the hydrogen economy.

Support programmes for hydrogen market development in Poland are mainly based on EU funds, sometimes increased by additional national funding. Funding is managed and distributed by relevant ministry or other governmental executive agencies. Big part of the national programs supports research and development of hydrogen projects, managed by National Centre for Research and Development (NCBiR) and National Fund for Environmental Protection and Water Management (NFOŚiGW). Executed programs of this type are described below.

“New energy” program aims to accelerate the energy transition process. Almost €600 million is intended for projects supporting the 6 main objectives of the program.[52] One of them, with financing of around €140 million is objective of production, transport, storage and use of hydrogen. Program support research and development of the hydrogen project, with the intent to allow for their commercialisation. It allows obtaining a loan of up to 85% of the project's eligible costs with the possibility of an innovation bonus of up to 20% of the loan principal disbursed, which doesn’t exceed €2.5 million.

“New energy technologies” is another research and development program, which allocates around €88 million for projects improving Poland’s energy security and decarbonization efforts. Hydrogen projects can benefit from two out of three parts of the program.[53] Around €33 million is dedicated to “technologies of production and utilisation of hydrogen” and another around €26 million to “construction of local energy storage in various technologies, integrated with RES”. Hydrogen projects related to production of hydrogen with the use of electrolysis powered by RES, biomass or waste gasification, high-temperature methane pyrolysis can apply for funding. Support can also be given to projects converting current fossil fuel energy systems to hydrogen-based systems and hydrogen energy storage projects integrated with RES. Funding is provided on a competitive basis, in three phases, increasing as projects move to the next phase. At the end, only one project remains in each of the three main categories.

Another ongoing hydrogen related research project is “GOSPOSTRATEG”, focused on the storage of hydrogen in salt caverns. Its role involves conducting socio-economic research to support decision-making in the formulation of national and regional development policies concerning large-scale hydrogen storage.[54] These storage facilities are intended to be key to ensuring the country's energy security and assisting in balancing of the national energy system. The maximum grant for a project is around €2.4 million.

Programs which focus on implementation of hydrogen solutions in transport are “Green Public Transport” with around €240 million available in grands and €47.5 million in loans[55] and “Support for electric vehicle charging and hydrogen refuelling infrastructure” with grants amounting to €204 million.[56] Both of the programs are financed by National Recovery and Resilience Plan (KPO) which is granted by the EU. The objective of the aforementioned programs is to facilitate the implementation of electric and hydrogen buses in Polish cities and the construction of 20 hydrogen refuelling stations.

Another recently introduced program, "Hydrogenation of the economy", is dedicated to the transport sector. Its objective is to facilitate the development of projects related to the construction, deployment, and commercialisation of hydrogen-powered vehicles.[57] The program is intended to provide support for research and to increase the production capacity of hydrogen technology manufacturers. The budget for achieving the programme's objectives is approximately €115 million in grants and €163 million in loans. The maximum grant amount is €35 million, while the maximum loan amount is €70 million.

More funding has been acquired by Polish low-emission hydrogen projects which will be described in chapter 3, however this funding origins from the EU funds. National funding is aimed mostly at research and development[Interview 10] and overall is not supporting the development of the hydrogen market in a way which would ensure that objectives of Polish Hydrogen Strategy are met. There is a lack of dedicated support programs for industry and large-scale hydrogen production projects. While it is beneficial to explore a range of hydrogen production methods with the potential to diversify production in the future, the overall level of support for hydrogen production is currently limited. The absence of support for large-scale hydrogen production projects and the implementation of hydrogen in industry may have adverse consequences for the future health of the Polish economy. [Interview 9] No other forms of support are available on the local government level or in the form of tax reliefs. [Interview 1].

It can be argued that the lack of greater support for hydrogen projects in recent years may be attributed to the blockage of the EU RRF fund for Poland. Financing was only resumed a year prior to the writing of this work. Consequently, some programmes could not be initiated in the previous years, and there was not enough time for new programs to be announced. Regardless of the cause, it can be observed that overall national support for the development of the hydrogen market is limited. Polish companies must compete for funding at the European level, which is problematic due to the high cost of hydrogen production in Poland.

The ambitious objectives of the EU and Polish strategies appear challenging to achieve, particularly in light of the specific circumstances of the Polish market and the lack of tangible support programs for the hydrogen market. The absence of proper legislation and a clear decarbonisation roadmap adds up to the difficulties facing hydrogen development. Despite these challenges, the Polish hydrogen market is developing, as detailed in chapter three.

Chapter 3: Developments of Low-emission Hydrogen Market in Poland

This chapter examines the current state of the low-carbon hydrogen market in Poland. It describes the ongoing development of hydrogen along its value chain in various sectors. The potential and ongoing involvement of authorities in the development of hydrogen technologies is analysed at various levels of governance, including national, regional, and local. Current and potential issues which could jeopardise the development of the hydrogen market in Poland are identified and analysed.

Hydrogen Production and Transmission: Current Developments and Key Stakeholders

Despite the difficulties in implementing hydrogen technology in Poland, the market for low-emission hydrogen is growing. New market development investments are planned or already in progress along the whole value chain (fig. 29). However, it can be observed that, the development, motivated by the specifics of the Polish market (decarbonisation pressure, state of transmission networks, need for energy storage, carbon intensity of transport, industry, and power & heat generation), is limited by issues regarding legislation, infrastructure and other challenges described in the previous chapters.

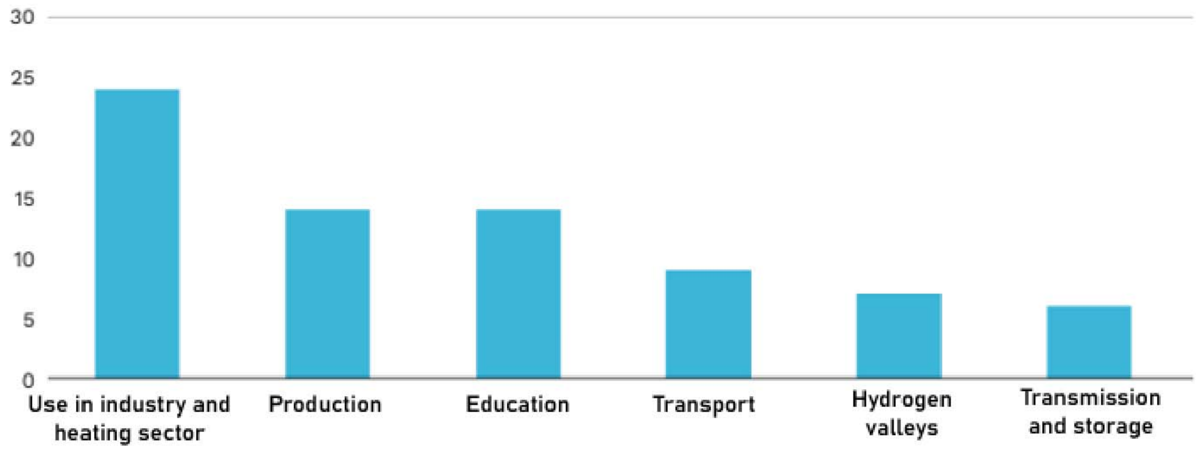

Figure 29: Hydrogen investments in Poland by type of entity activity (number of entities). [11]

Large-scale hydrogen production projects are being pursued by larger companies that have received support from European Union funds. Some of them use grey hydrogen in their production processes and it is in their strategic interest to implement green hydrogen. Others are related to the power generation sector and want to use their position on the RES market to produce low-emission hydrogen.

At the time of writing this work, most of the hydrogen production projects under construction are of a low capacity and do not represent significant volumes.[Interview 10] However, there is considerable interest in the production and use of hydrogen by both large and small companies. When analysing the development of the hydrogen market in Poland, there are two companies that are particularly at the forefront of the market.

A major company involved in the development of the hydrogen market is Orlen Group, the biggest Polish company. It is best known for its refining activities and operation of the network of petrol stations in Central Europe (Poland, Germany, Czech Republic, Slovakia, Lithuania). Its portfolio also includes the petrochemical, energy, and mining sectors. Although the hydrogen sector is not their core business, they are one of the largest producers of hydrogen in Poland, which they use for their own consumption. The development of low-carbon hydrogen is one of the objectives of the company's strategy. They intend, among others, to commission 540 MW capacity of low-emission hydrogen and develop at least 100 hydrogen refuelling stations. 57 of those stations are to build in Poland, 28 in the Czech Republic and 26 in Slovakia. Orlen plans to use a wide range of methods to produce hydrogen. The company wants to utilise RES generation for the electrolysis purposes, use biomethane, municipal waste and enhance the steam methane reforming processes used today, with CCS. Hydrogen produced is to be used in its petrochemical and refining processes, in the chemical industry and in transport sector. The funding allocated for these purposes' amounts to around €1.7 billion (fig. 30). Besides this funding, most of the big hydrogen projects developed by Orlen are also seeking additional external funding in the range of 40-80% of the total cost.

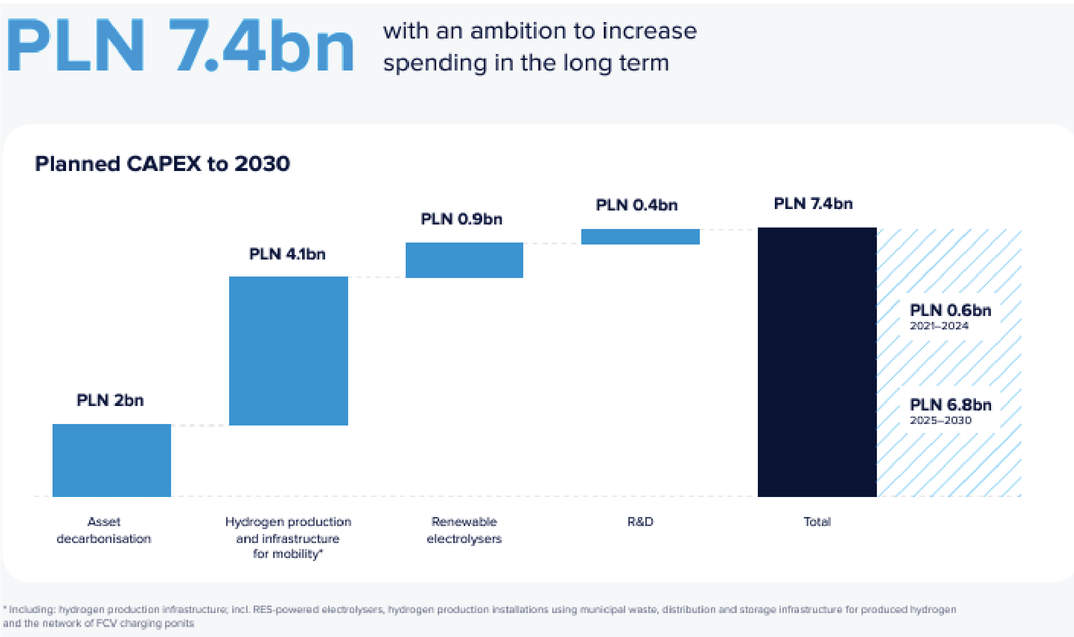

Figure 30: Orlen - planned hydrogen development Capex by 2030. [58]

Orlen is a significant company on the hydrogen market in Poland, not only because of the size of its investment, but because its activities cover the entire hydrogen value chain. Orlen invests in various methods of hydrogen production, both small and large scale, utilises hydrogen and builds hydrogen refuelling stations. The company participates in the development of the four hydrogen valleys and owns a laboratory, by which the quality of the hydrogen produced can be tested and certified (Anwil laboratory).[59] A significant accomplishment for the Orlen Group was the attainment of IPCEI status (Important Projects of Common Interest) for the Hydrogen Eagle project, which aims to enhance hydrogen production capacity and construct refuelling stations throughout the EU (fig. 32). The IPCEI status allows EU countries to provide additional financial support to projects, which struggle to develop due to the big financial risks and the scale of the projects but have a positive impact on the entire EU society and are in line with the common EU objectives.

Figure 31: Orlen hydrogen strategy goals up to 2030. [58]

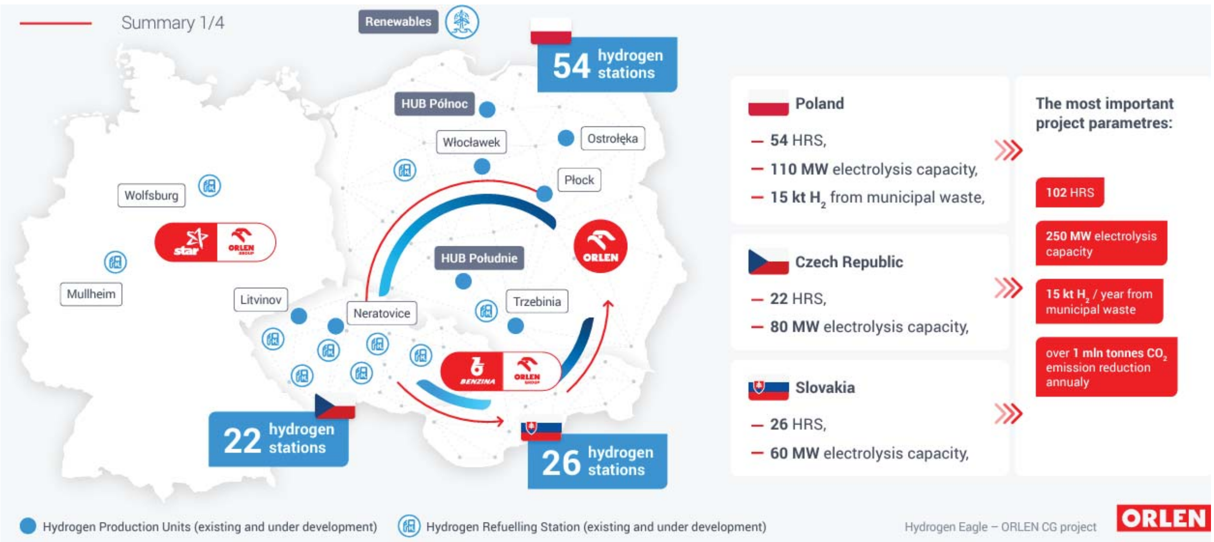

Figure 32: Hydrogen Eagle Project summary. [60]

Another significant player in the hydrogen market is ZE PAK (Zespół Elektrowni Pątnów-Adamów-Konin SA belonging to Polsat Plus Group). It is the largest private energy group in Poland, dealing mainly with activities in the mining sector and the production of electricity from both conventional and renewable sources. The company is investing extensively in hydrogen technology. It is building electrolysers that will be powered by electricity generated from biomass, is investing in hydrogen refuelling stations and has a company dedicated to the manufacturing of hydrogen buses (PAK-PCE Polski Autobus Wodorowy). It is also planning to build alternative fuels laboratory and a fleet of more than 150 hydrogen cars is already operating within the group's subsidiaries.[61] Between 2021 and 2026, the company plans to invest more than €115 million in the hydrogen sector.

Other companies interested in the low-carbon hydrogen production market include state-owned energy companies but also private companies like Polenergia and Synthos Green Energy. Low-emission hydrogen production also appears in the development strategy of Poland's largest hydrogen producer, the Azoty Group, but details of investments in the field are not yet officially known.

Table 7 provides a closer look at some larger ongoing projects in Poland. The funding presented in the table relates not only to the construction of the electrolyser systems, but also for other measures included in the objectives of the projects, such as the construction of RES capacity, hydrogen refuelling stations or infrastructure for the utilisation of the produced hydrogen. |The total number of planned projects is much higher. There is a lot of information about ongoing consultations on technical and economic analyses or signed letters of intent declaring the intention to produce hydrogen at various sites. However, these projects are generally smaller (around 1MW-5MW electrolysis). The table below shows projects that are more reliable, larger in scale or have received funding.

Table 8: Selected hydrogen production projects in Poland.

Company	Hydrogen Production Capacity	Fuel	External financing	Comments
Orlen	100-300 MW, in progress	Offshore, onshore wind, municipal waste, PV	€62 million - Connecting Europe Facility Fund	Hydrogen Eagle Project objective, in Poland, Slovakia and Czech Republic
Lotos Green Energy H2 (Orlen)	100 MW, during construction	Solar power 50MWp + battery storage 20MW	€158 million - EU Innovation Fund	H2 for refinery purposes, to be increased to 1GW by 2030 and 4GW by 2040
ZE PAK	5MW, during construction	Biomass	€4.5 million – EU Innovation Fund	Delayed due to safety issues, to be increased to 100 MW
Polenergia	105MW, possibility of obtaining financing	Local RES	€142.77 million – max potential funding due to IPCEI program	For heavy industry and transport purposes
Synthos Green Energy	No data	Local RES	€4.5 million – European Funds for a Modern Economy	Hydrogen production projects sponsored via FENG program

It can be seen that there are few large-scale hydrogen production projects in Poland and unless this situation changes quickly it will be difficult to achieve the objectives of the Polish Hydrogen Strategy. This is mostly because at the moment hydrogen production is expensive and investments require additional financial support. More dynamic development of the small-scale hydrogen production market can be observed in Poland. Small projects have a greater potential to be situated in a favourable geographic area, benefiting, for example, from low prices of energy generated by local RES Smaller investments require less capital, and the smaller-scale electrolysis technology is more technologically mature. [Interview 8] Another factor contributing to the phenomena is lack of hydrogen transmission infrastructure.

At the moment, there is no possibility of transporting hydrogen in Poland using the national natural gas transmission networks. Hydrogen blending can be conducted in negligible quantities, which may cause problems on the part of sensitive consumers and have a negligible decarbonising effect (fig. 33). Currently available solution, is to transport hydrogen using hydrogen trucks ('tankers') or containers, which has been in common use for years and does not involve security risks.[Interview 6] However, it has never been developed on the scale needed to ensure a continuous supply of hydrogen for current industrial demand or, even less, the projected demand for hydrogen by the Polish Hydrogen Strategy. In addition, the financial viability of this type of hydrogen transport is limited to around 200-250 km due to the technical characteristics of hydrogen.[Interview 6] The lack of dedicated hydrogen infrastructure of pipelines, which allow for the cheapest transmission of hydrogen in the long term, is contributing to decelerated hydrogen market development.[62]

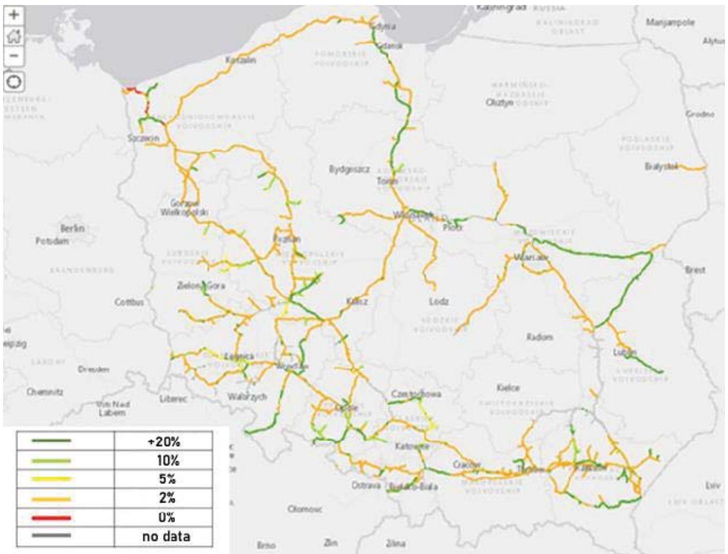

Figure 33: Allowable hydrogen content in individual sections of the transmission system. [63]

Currently, there are two companies in Poland carrying out activities concerning the development of hydrogen transmission networks (both state-owned) – PSG (Polska Spółka Gazownictwa) and GAZ-SYSTEM.

PSG is the gas distribution grid operator in Poland. It operates throughout the entire country, distributing natural gas through more than 210,000 km of pipelines. In late 2020, the company joined a partnership with another major Polish gas company (PGNiG – Orlen Group) to build a hydrogen economy. PSG was the first company in Poland to obtain a technical approval certificate for the transmission of natural gas with a hydrogen blend of 20% in the 7 km section of the pipeline. Furthermore, it has initiated a collaborative venture with the German gas distribution operator Gasnetz Hamburg. The objective of this partnership is to facilitate the exchange of expertise in the field of hydrogen transmission, as well as the development of competence within the company in the construction of hydrogen pipelines.

GAZ SYSTEM is Polish gas transmission system operator (TSO), managing a transmission pipeline network of more than 10,000 km. The company is investigating the level of interest in transporting hydrogen via the transmission network among consumers and producers. GAZ SYSTEM's determination to develop a national hydrogen network is evident through the Hydrogen Map of Poland project (Wodorowa Mapa Polski). Analysis carried out during the project will enable the creation of an infrastructure development plan taking into account volume, geographical and time related factors. The project's objective is to identify market needs, enable the study participants to develop in line with the envisaged network design and, in the future, to construct the efficient hydrogen pipeline network.

With the inclusion of hydrogen transmission and storage projects in the EU's TEN-E (Trans-European Energy Networks) regulation in 2022, the company has applied for PCEI (Projects of Common Interest) status for its three hydrogen projects. PCEI status is given to projects important for achieving EU goals and fostering regional cooperation. In the case of GAZ SYSTEM's projects, it would make it possible to obtain additional funding from the EU's CEF fund. Two projects concerned the construction of hydrogen pipeline infrastructure, connecting national producers and connections with final consumers, and the construction of hydrogen storage in the city of Damasławek. A third project, Nordic-Baltic Hydrogen Corridor has been granted PCEI status. It is being developed by 8 natural gas TSOs and aims to construct a hydrogen pipeline going through Finland, Estonia, Latvia, Lithuania, Poland, and Germany (fig. 34). The analysis of the conditions for the development of the project is to be completed by mid-2024 and the entire project is to be implemented by 2030.[64]

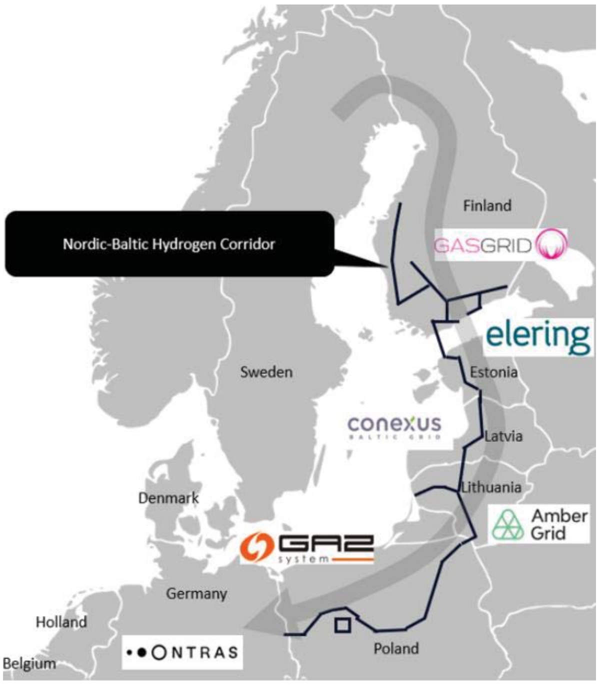

Figure 34: Planned route of Nordic-Baltic Hydrogen Corridor. [64]

The construction of a national hydrogen transmission network in Poland supported by storage facilities is crucial for the development of hydrogen technology in the internal market. At the moment, from a market perspective, it is more economical to produce and consume hydrogen locally than to transmit it through pipelines.[Interview 8] However, as the hydrogen market develops, a transmission network will be required and failure to build it may have a significant impact on the stagnation of the development of the hydrogen market. Large infrastructural projects enable to bring together hydrogen market stakeholders, reduce the risk on individual actors and allow to faster develop the hydrogen market.[Interview 8]

Projects that enable international connections are an important element of the hydrogen market. They help ensure the security of supply and demand and stabilize hydrogen prices by enabling cross-border exchange and fostering a unified European hydrogen market. Projects in this area are already being implemented in Poland (Nordic-Baltic Hydrogen Corridor). New initiatives are being studied, like for example connecting Poland to planned Central European Hydrogen Corridor (fig. 35). National governments support and cooperation between gas grid operators is a key to implementation of cross border projects which can trigger investments and have big impact on the development of the hydrogen market.

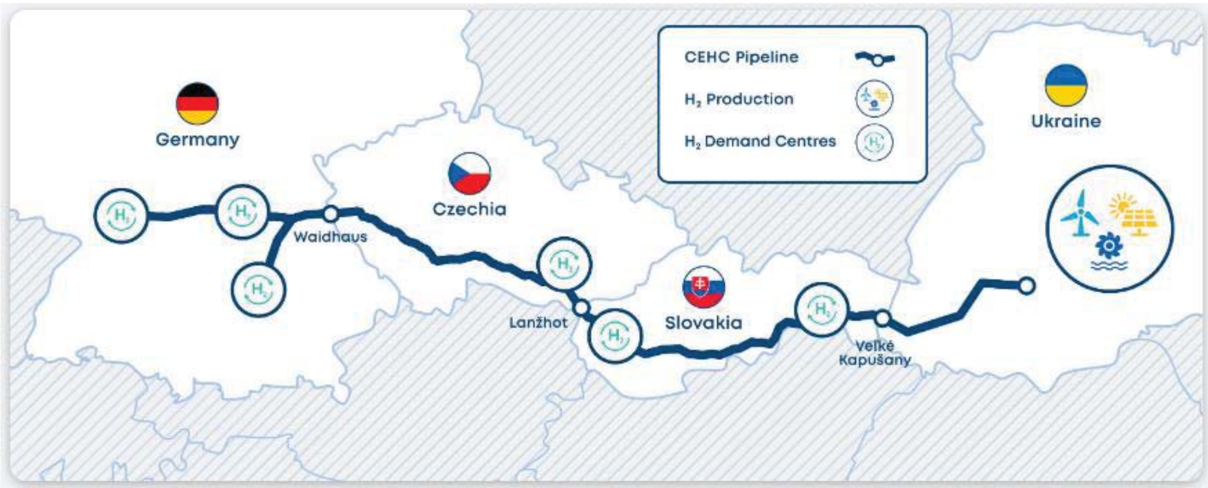

Figure 35: Planned route of Central European Hydrogen Corridor. [65]

A review of the development of large-scale hydrogen production and the hydrogen transmission sector in Poland reveals that developments in these sectors are the responsibility of the national government, state-owned companies, and some large private companies.

The national government is responsible for creating regulations and policies to support the development of hydrogen technology, enabling the conditions for projects implementation, and allocating funds for key infrastructure initiatives. It also has the ability to bring together national and international stakeholders. Part of these tasks are carried out by the Hydrogen Technology Committee of the National Chamber of Commerce. [66] It focuses on collaboration with international bodies involved in the development of hydrogen technology, such as

Hydrogen Europe and the Hydrogen Council. Additionally, the Committee serves as Poland's representative on matters pertaining to international hydrogen market. The core competence of large public and private companies is the development of hydrogen production on an industrial scale and the implementation of strategic projects with the objective of ensuring supply security and reducing the cost of hydrogen production.

Hydrogen Utilization Market Development and the Role of Subnational Governance

The hydrogen market in Poland is also developing in sectors other than large-scale hydrogen production and transmission. The coordination of these activities is the competences of regional and local governments.

In Poland out of 16 voivodeships only 6 mention hydrogen in their regional development strategies. One regional hydrogen development strategy has been implemented and one is being developed. In the remaining 4 voivodeships, individual, brief mentions of hydrogen can be found in regional development strategies (table 9).

Table 9: Hydrogen in regional development strategies in Poland.

Voivodship	Scope of hydrogen implementation in regional strategies
Greater Poland	Full regional hydrogen strategy implemented.
Lesser Poland	Regional hydrogen strategy during development.
Lower Silesia	Mention in the regional energy strategy of hydrogen as an energy storage option and innovative R&D direction.
Lublin	In the list of initiatives to implement the regional strategy, a project to produce green hydrogen for the chemical industry and transport was identified as strategic.
Łódź	As part of the innovation objectives of the regional development strategy, the need to adapt the gas network to transport alternative fuels (the aforementioned hydrogen) was mentioned. An acknowledgment of hydrogen potential as the energy storage.
Masovian	Mention in the regional development strategy of developing the use of alternative fuels in the economy, especially those based on hydrogen. Willingness to increase the share of electric and hydrogen vehicles in transport.

The lack of regional hydrogen strategies or precise hydrogen objectives in regional development strategies is not a good approach from the perspective of hydrogen market development. Actions related to the development of the hydrogen market should be planned at every level of governance, which would allow for transparency and make it easier to monitor and implement the objectives of the Polish Hydrogen Strategy. Fortunately, the lack of such initiatives does not mean that Marshal Offices are passive with regard to the development of hydrogen technology. An example is the "Declaration of Interregional Cooperation to Establish a National Hydrogen Base Network", which was signed by the authorities of the West Pomerania, Lesser Poland, Lower Silesia and Lubusz voivodships. Although as many as two of these four regions do not include hydrogen in their strategies, they have taken the initiative to support the implementation of hydrogen technology in Poland. The declaration specifically aims to connect these voivodships to hydrogen pipelines that bypass Poland (fig. 35,36). Regional authorities are also involved in the development of the hydrogen market at the hydrogen valleys level, as representatives of respected regional governments are the member of each of operating hydrogen valley.

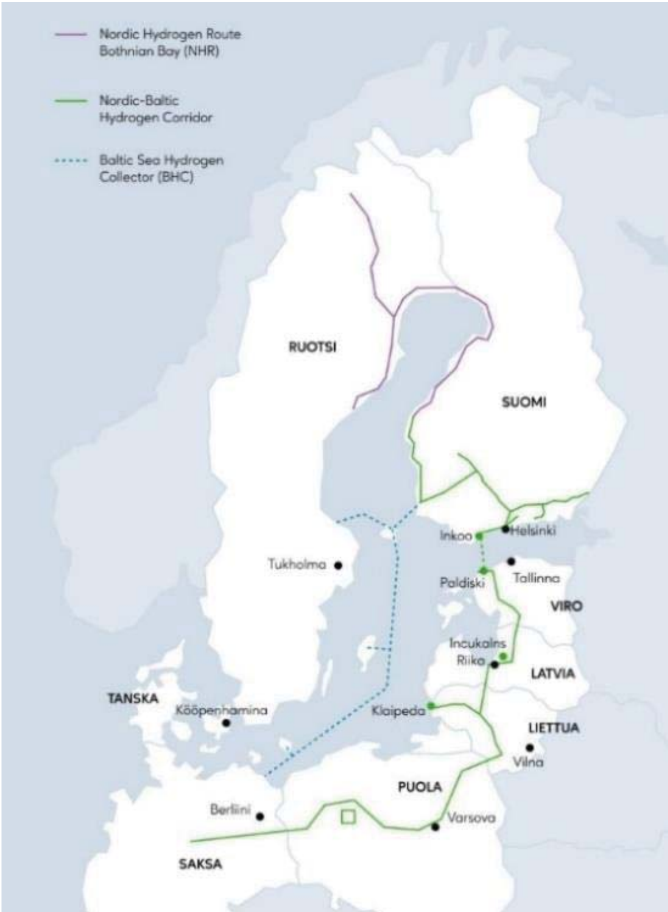

Figure 36: Planned hydrogen pipelines in the Baltic Sea. [67]

The commonly accepted definition of a hydrogen valley states that a hydrogen valley covers a defined geographical area where hydrogen serves more than one end-user or application (example in the mobility, industry, and energy sectors), entire hydrogen value chain is secured and the valley has a minimum capital investment of €20 million.[68] In Poland, in addition to this definition, another model for the functioning of the hydrogen valley has emerged in the form of associations. They focus on bringing together investors, the banking sector, academia, and government representatives to develop concepts for implementing local hydrogen projects. The distinction lies in the fact that they are not necessarily implementing hydrogen technologies at this point in time.[Interview 9] These organizations operating in the form of associations, advisory councils or clusters have adopted the hydrogen valley name, but do not fit into the before mentioned definition.

The approach of this kind of hydrogen valleys is based on the examination of local sectors for the potential implementation of hydrogen technologies, with the subsequent creation of initiatives designed to facilitate such implementation. At this time, it is uncertain whether their actions will have a significant impact on the development of the hydrogen sector in the short term. In some cases, these valleys are located in regions that lack the optimal conditions for hydrogen production or have been unable to secure the necessary funding. However, in the long term, for example, as the hydrogen market develops and the price of hydrogen declines, they have the potential to become a significant accelerator in the development of hydrogen technologies – implementing hydrogen based on the analysis and consultation they are currently undertaking.

Figure 37: Hydrogen valleys in Poland 2024. [69]

For a hydrogen valley to effectively implement the goals of hydrogen production and utilisation, it must have the right conditions and be properly managed. The success of a hydrogen valley largely depends on the very first stage of the hydrogen valley's creation, i.e., the selection of a suitable location. It must be situated in an area with favourable conditions for hydrogen import or low-carbon energy production (good conditions for RES generation, access to biomass or nuclear energy) and be in proximity to a market for the hydrogen produced.[Interview 9] It is also crucial for the hydrogen valley to bring together committed members from different sectors who can enable the development of the hydrogen valley in a wide range of areas. It is important to cooperate with different actors, such as regional and local government, energy companies, transmission system operators, hydrogen consumers, research, and science institutions and the local community.[Interview 3]

Another critical feature of a hydrogen valley is its ability to obtain funding, which significantly determines the scope of its activities. Hydrogen valleys are sponsored internally, by contributions from members of the association, or externally by national or EU financial support. If a hydrogen valley is unable to obtain external funding and does not have members willing to invest in its activities and expansion, it will not achieve significant results. [Interview

10] Cooperation with the government and the EU is crucial in order to develop the valley in line with the objectives of the national and EU strategy and to be eligible for financial support. [Interview 3,9] Once funding has been secured and actors willing to participate in hydrogen projects have been brought together, it is important to properly manage the hydrogen valley activities[Interview 10] and to actively seek feasible applications to create demand for the hydrogen produced.[Interview 9]

A number of hydrogen technology manufacturing companies are present on the Polish market, and the hydrogen valley can serve as a bridge between the manufacturers and potential regional customers from different industries. It is worth to mention Polish companies implementing hydrogen in transport. Companies which offer hydrogen buses manufactured in Poland include PAK-PCE Polski Autobus Wodorowy or ARP E-Vehicles. One of the first hydrogen-powered locomotives (hydrogen fuel cell with battery) was also patented in Poland by PESA Bydgoszcz company. The vehicle is permitted to operate and is well suited to decarbonise traction sections which are difficult to electrify. There are also many companies offering systems, equipment, and components used in hydrogen sector, as well as providing research, consultancy, and scientific services. An analysis of these companies is beyond the scope of this work, but it should be noted that developments in this area of the hydrogen economy in Poland are also progressing. Hydrogen Valleys can be a significant actor enabling these companies to expand production and attract new, seeking to decarbonise customers.

Activities carried out in hydrogen valleys provide a well-rounded overview of the sectors that will implement hydrogen technologies in Poland. The greatest potential is to use hydrogen to decarbonise industry[Interview 1,6,9,10] and transport, especially heavy and public transport[Interview 1,6, 10]. Hydrogen will also find applications in places such as harbours and logistics centres[Interview 1]. Due to Poland's geographical location, hydrogen will also be implemented in the heating sector,[Interview 1, 6] and because of the state of the power transmission networks, it may be beneficial to the energy sector[Interview 6,10].

Table 10: Selected hydrogen valleys considering the designated hydrogen utilisation sectors.

Hydrogen valley	Hydrogen utilisation sector
Amber Hydrogen Valley	Industry – use in: 2 harbours (forklift trucks, terminal tractors), refinery processes, production of ships and construction materials Transport – supplying: hydrogen locomotives, road transport, the city's waste collection vehicles and hydrogen buses,
Lower Silesian Hydrogen Valley	Industry – chemical sector (ammonia), metallurgical industry (green coper) Transport – public transport (buses), river transport (hydrogen barges) Agriculture – hydrogen agricultural machines Transmission – hydrogen in gas networks
Greater Poland Hydrogen Valley	Power and heating – hydrogen in district (CHP) and individual heating Transport – use in aviation and public transport
Silesian-Lesser PL Hydrogen Valley	Industry – chemical (glycol), metallurgical industry (steel) Transport – public transport (buses)
Masovian Hydrogen Valley	Industry – chemical and petrochemical (synthetic fuels), Transport – public transport, hydrogen locomotive, hydrogen trailers
Central Hydrogen Valley	Transport –logistics centres, heavy transport public transport, rail transport Power generation – hydrogen ready gas turbines

Hydrogen valleys are strategic clusters propelling the development of the hydrogen economy in Poland. They are able to utilise the full potential of RES generation in the given regions, which would otherwise be difficult to distribute to consumers via transmission networks. In addition, they produce and consume hydrogen locally and therefore do not require a national hydrogen transmission network for their operation and development. Ultimately, they may be connected by a hydrogen transmission network to form a national hydrogen market.

Through their potential for utilising local energy generation and the finding local hydrogen applications in various sectors, hydrogen valleys are said to be a means to enhance, if not completely ensure, energy security. [70] To achieve that, they would need to supply reliably available hydrogen to consumers at a low, fair price and have a secure value chain regarding the materials and equipment used for hydrogen production.[71] However before that can be achieved price of hydrogen must be lowered through appropriate policy, supporting hydrogen technology and trade agreements regarding critical materials needed for production of RES and hydrogen systems must be secured.[Interview 3] In the future, when hydrogen market develops, hydrogen valleys can be an important part of energy system and play a significant role in ensuring energy security.

Last however one of the most important functions of the hydrogen valley that was mentioned by the experts, enabling the implementation of hydrogen projects, is cooperation with local authorities and the local community.[Interview 3,9] Without the social acceptance of the local community, hydrogen valleys will not be able to function and the goals of hydrogen strategies cannot be achieved.[Interview 3] More detailed analysis of the aspects of social awareness and acceptance in Poland is provided later in the work, but it is the responsibility of the Hydrogen Valley to ensure public awareness and education about hydrogen by involving the local municipality and local government.

The role of local governments in the development of the hydrogen market does not end with their participation in hydrogen valleys. Local authorities or their subsidiaries are already involved in implementation of projects utilising hydrogen in city's district heating – 1.800 flats in Środa Śląska, 195 flats in Śrem. Hydrogen heating concepts are also being explored in Piła, Czarny Dunajec and Wałcz. Another initiative involving local authorities is the "100 MW H2" project, which aims to develop 100 one-megawatt electrolysers to create local community eco-systems for the purposes of heating and local industry.[72]

Particular contribution of local authorities to the implementation of hydrogen technology can be seen in the transport sector. A number of municipalities and cities are choosing to decarbonise public transport using hydrogen buses. Investments in hydrogen transport also involve the development of hydrogen refuelling stations and dedicated hydrogen vehicle maintenance sites. A map of planned, implemented and completed investments in hydrogen refuelling stations and urban bus fleets in Poland is presented in figure 38. It should be updated with the exact location of new 54 hydrogen refuelling stations to be implemented by Orlen thanks to EU funding for the Hydrogen Eagle project and 5 new stations to be implemented by ZE PAK. The exact locations have not yet been confirmed. It should be mentioned that a large proportion of the projects shown on the figure 38 are planned projects (orange and brown colour). In terms of refuelling stations, more than half of the 62 stations included are estimated locations of refuelling stations planned for implementation in accordance with the Alternative Fuels Infrastructure Regulation and some of them may be constructed via Orlen's Hydrogen Eagle project.

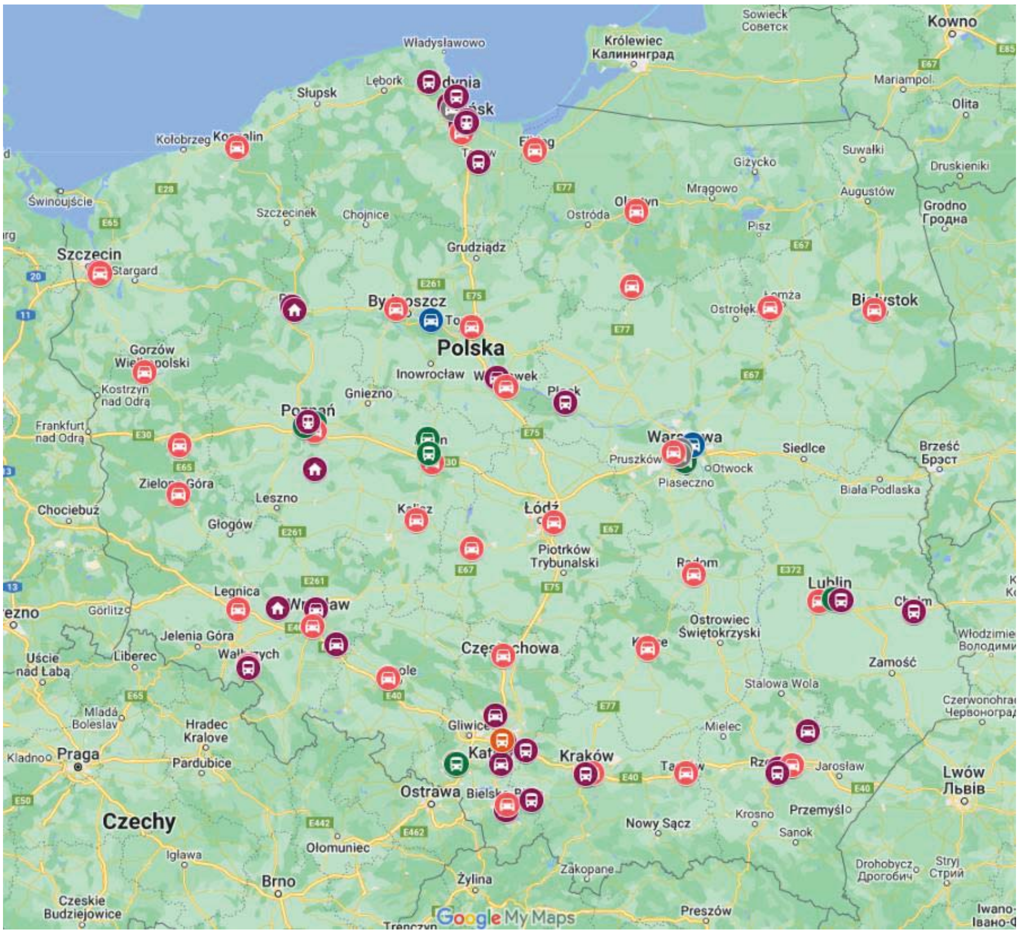

Figure 38: Investments in hydrogen refuelling stations and urban bus fleets in Poland 2024. [73]

A factor having a big impact on the development of hydrogen technologies in transport is certainly the national funding earmarked for the development of green transport and other funding that individual regions can apply for (example Just Transition Fund in Silesian region, Project Development Assistance in Gdansk). However, it is local authorities that are responsible for the organisation of public transport in their area and the choice of hydrogen vs. electric vehicles in this field shows that the advantages of incorporating hydrogen into public transport are being noticed in Poland. Hydrogen bus fleets are already present in 4 Polish cities, and the remaining 16 are making investments in this area (example: Poznań 84 buses, Chełm 26 buses, Wałbrzych 20 buses, Piła 10 buses).

It is clear that not all planned projects will be realised. Some examples of the abandoned projects to use hydrogen for district heating are investments in Kamień Pomorski and Środa Wielkopolska, or the lack of applications for the tender auction to manufacture hydrogen buses in Piła.

Looking at the rate of development of hydrogen production projects, achieving the goal of 2 GW of electrolysis capacity in 2030 seems distant. However, from the number of investments carried out and planned, it is clear that regional and local authorities have an important part to play in the development of the hydrogen sector in Poland. The elements of the Polish Hydrogen Strategy that have received government funding (especially the transport sector) are developing significantly and have a fair chance of meeting the objectives. The number of hydrogen valleys is greater than planned for 2030 and their activities are introducing hydrogen solutions to consideration in various sectors of the economy. Initiatives to build a hydrogen network and international connections are emerging. Polish companies are developing technologies for the use of hydrogen on both the demand and supply side. Large scale hydrogen projects developed by Polish companies are recognised on the international stage and obtain EU funding.

Overcoming Barriers to Hydrogen Market Development in Poland

This paper has already discussed some of the identified problems that negatively affect the development of the hydrogen market in Poland. These include the challenges of financing hydrogen projects, lacking tangible support for the hydrogen economy, and the missing hydrogen transmission infrastructure, which leads to the implementation of individual, disparate projects.

Another current obstacle to the development of a national hydrogen market is the state of the Polish hydrogen-specific legislation.[Interview 6,7,10]. Years after the introduction of the Polish Hydrogen Strategy, one of its key objectives has not been achieved, namely the introduction of a stable and transparent regulatory environment for the development of the hydrogen market in the country.[74] Legislative shortcomings lead to a lack of transparency in the requirements for the technical specifications of hydrogen projects and to decision-making dilemmas at the level of approving project implementation.[Interview 6] This was reflected in delays in obtaining the relevant executive permits and discouraged investors from entering the hydrogen market.[Interview 10]

Lack of legislation has affected the development of the entire value chain of the hydrogen economy.[75] There was no legal definition of hydrogen, which meant that hydrogen could not be directly recognised as a gaseous fuel and created problems for hydrogen projects involving hydrogen generation, as well as its use in the gas grid and energy storage (above and below ground), or hydrogen sale to end users. Significant was also lack of technical specifications for the construction and use of hydrogen refuelling stations and relevant on-site hydrogen storage. This has led to a situation where hydrogen projects have adapted technical parameters to meet regulatory requirements available in other countries or have not been qualified as facilities utilising hydrogen in the energy sector.

The Ministry of Climate and Environment has announced, in early 2024, that work is underway to implement the necessary hydrogen legislation in the Energy Act and other related regulations. The new regulations will ensure that investment risks are reduced, and that clear legislation is introduced to encourage investment in the hydrogen sector. This will be achieved by, among other things, introducing hydrogen transmission and distribution operators (recommended by Interviewee 4), simplifying construction regulations (recommended in Interviewee 10), and clarifying the rules for combining natural gas and hydrogen activities. The new hydrogen economy legislation is to be in enforced at the end of 2024 and addresses these issues. Proper shape and implementation of these regulations will be crucial for achieving the objectives of the Polish Hydrogen Strategy.

The issues related to the hydrogen economy, which will be discussed later in this chapter, do not currently have a significant impact on the hydrogen market in Poland at the moment. However, if they are not addressed, in the long term they may have a considerable impact on the pace of hydrogen market development or even completely prevent the implementation of hydrogen projects.

The first aspect is the required number of new jobs that will be created when a hydrogen market develops in Poland. The creation of new jobs by the hydrogen economy can be heard as an argument for the development of the hydrogen market, but this is not necessarily the case. The number of new jobs depends on the rate of market development, and it is difficult to predict exactly how fast hydrogen market will develop.[Interview 8]

However, if we assume that the market will develop as rapidly as required to meet the objectives of the European and Polish Hydrogen Strategies, a situation may arise where, despite adequate financial outlays, political will and the involvement of contractors, there may not be enough skilled workers to manufacture the equipment and implement the hydrogen projects. The Polish market is in a favourable position in this respect, as hydrogen is already used in the economy and companies have experienced staff in hydrogen utilisation and transmission.[Interview 8] In addition, the Polish technical sector is well familiar with combustion processes and switching to hydrogen fuel in this respect will not pose a major challenge in terms of acquiring new skills (combustion processes in conventional power plants and CHP plants). However, the Polish industry has much less experience with the construction and operation of electrolysers. As the operation of electrolyser can be automated, it partially reduces this problem but does not solve it completely.[Interview 10]

Uncertainty about the pace of development of the hydrogen market and whether to wait for the market to develop first and risk a shortage of manpower, or to develop a potentially large workforce for the market without knowing whether the market will need it, is another dilemma associated with the development of the hydrogen.[Interview 8]

Regardless of the pace of market development, the education of experts and specialists in hydrogen technology is important. Particularly noticeable in Poland is the lack of hydrogen courses in vocational schools or technical schools.[Interview 11] These are significant technical jobs needed both for the implementation of hydrogen projects and their subsequent operation and maintenance. In the education sector, the first approaches to introduce such courses in secondary schools are taking place.[Interview 11] There are also initiatives, such as Hydrogen Academies organised by hydrogen companies and valleys as well as new university courses on the subject of hydrogen technology. Significant top-down intervention in the education sector, with moderate hydrogen market development, may not be needed as schools themselves have the potential to adapt their courses to current market trends.[Interview 10]

Education plays a key role not only in building competence in hydrogen technology and the market but is also crucial in educating the public and increasing public awareness of hydrogen.

This is a crucial aspect of the development of the hydrogen market, which is not adequately developed or even developed at all in Poland at the moment.[Interview 8, 11] The vast majority of people have a very basic knowledge about hydrogen and do not identify it with the energy sector. [76] In the research conducted, it was shown that hydrogen technology is perceived positively after a brief introduction. It is associated with RES, for which public acceptance is growing each year. The biggest hotspots for hydrogen technology identified in the study are reluctance to incur the additional costs associated with the hydrogen transition and safety issues. Education about the risks and benefits of hydrogen is particularly important in an age of misinformation and fake-news.[Interview 11] Hydrogen could repeat, in the future, the fate of some Polish waste utilization plants, whose projects face ongoing problems of public disapproval and protests from local communities.

The good thing is that people want to learn more about hydrogen.[Interview 2,11] Despite the lack of understanding of the technical details and the small number of real-life examples of hydrogen technologies in operation, people are curious about what the technology is and how it will affect their lives. Honest and transparent dialogue, communicating both the advantages and disadvantages of hydrogen, is key to achieving public acceptance towards hydrogen.[Interview 2,11]

Conclusions

Hydrogen is anticipated to play a pivotal role in the European Union's efforts to achieve its decarbonisation goals. Nevertheless, there are significant obstacles to the full realisation of the potential of a hydrogen economy. The future significance of hydrogen in the European economy will depend on the actions taken by the European Commission and the national governments of EU member states in the near future. The Multi-Level Governance framework has been applied to this study in order to identify the actors responsible for addressing the challenges that must be overcome in order to enable the efficient development of a hydrogen economy in Poland.

At the supranational EU level, there is a strong decarbonisation pressure and a growing commitment to integrating hydrogen into various sectors of the economy. However, the high cost of hydrogen and hydrogen technologies, lack of adequate generation capacity, and infrastructure absence are issues that the EU is beginning to recognise and address. With increasing requirements for the use of RFNBO in the energy mixes of the member states, we also see the introduction of more funding schemes for the development of the hydrogen economy. It is debatable whether the level of support is sufficient to achieve the EU strategy's goal. Nevertheless, some projects related to, for example, supporting the construction of electrolyser capacities and international hydrogen transmission infrastructure are receiving EU funding.

At the national level, the EU hydrogen strategy has been well implemented in the form of the Polish Hydrogen Strategy. Hydrogen is envisaged to be implemented in various sector of the economy. The development of the hydrogen market in Poland is directly dependent on the new RES capacities but it is also motivated by this development as it can support the operation of transmission networks. The tasks facing the national government in developing the hydrogen market in Poland include the full implementation of national hydrogen strategy, which involves implementing actions beyond the document itself. For the hydrogen economy to reach its potential in Poland, a comprehensive review of existing regulations is essential to identify and amend barriers to hydrogen development, ensuring clarity and efficiency in the approval process for new projects.

Grey hydrogen is currently a significant part of Polish, and the substitution of this with low-emission hydrogen is essential for the future competitiveness of Polish industry. Hydrogen also has the potential to become relevant in other sectors of the Polish economy. The national support systems that have been introduced are effective. Hydrogen transport in Poland, especially in the public sector, is developing rapidly. It is recommended that this support be extended to other sectors of the hydrogen market, such as the heating sector or energy-intensive industries. This would enable the decarbonisation of these sectors and accelerate the development of the hydrogen market. Financial mechanisms, including targeted funding streams, public-private investments, and tax incentives, should be established to reduce financial barriers and attract investments in hydrogen technologies.

Initiatives aimed at establishing a national hydrogen transmission and distribution network, which could later be connected through international connections with other EU countries, have the potential to stimulate the growth of the hydrogen market. The development of a national infrastructure plan for hydrogen, which takes into account the production facilities, consumers and a transnational hydrogen grid, could enhance energy security and improve the conditions of the hydrogen market. During the period of hydrogen network development, it is recommended that the national government provide support to local initiatives in the production and consumption of hydrogen, as well as to larger companies that are striving to build their hydrogen portfolios. While local initiatives are driving the initial phases of hydrogen adoption in Poland, and large-scale hydrogen generation projects are being pursued to ensure stable hydrogen supply, national government support is critical to scaling up these efforts.

The number of planned small and medium-sized hydrogen investments shows how important the role of regional and local governments is in developing the hydrogen market. Introducing hydrogen into regional development strategies or implementing dedicated regional hydrogen strategies could have a positive effect in encouraging investors to use hydrogen in regional industry and enterprises. Although most such documents are lacking, regional governments already play a key role in bringing together regional stakeholders and developing the hydrogen valleys.

Hydrogen valleys currently have the greatest potential to develop hydrogen technologies in Poland, regardless of the structure of the valley's operations. Their effectiveness will determine the future pace of creation of a national hydrogen market. Furthermore, these valleys should actively seek support at the European level, tapping into EU funding programs such as the Hydrogen IPCEI (Important Projects of Common European Interest) and the Horizon Europe research and innovation framework. Such support can help to align regional efforts with broader EU goals, ensuring that Poland's hydrogen initiatives are integrated into the larger European hydrogen network.

Local governments have the potential to implement small hydrogen projects in places where hydrogen development is most cost-effective, outside of hydrogen valleys operation. This localized approach can lead to the efficient and targeted deployment of hydrogen technologies, capitalizing on specific regional strengths and resources. These projects can act as catalysts for broader adoption, showcasing practical applications and building the case for further investment in hydrogen technologies. By initiating pilot projects such as hydrogen-powered public transportation, municipal energy storage systems, and community hydrogen refuelling stations, local authorities can drive immediate and tangible benefits, demonstrating the viability and advantages of hydrogen solutions to the public and private sectors alike. Along with hydrogen valleys, local governments play a crucial role in disseminating information and educating the public about the benefits and safety of hydrogen energy, which is vital for overcoming any resistance to new technologies.

Education on hydrogen is very low in Poland and should be developed at every level of governance along with the development of the hydrogen market. For Poland to fully realize the potential of hydrogen, it is imperative that education on this subject be expanded and integrated. By prioritizing hydrogen education, Poland can build a skilled workforce capable of driving innovation and supporting the development of the hydrogen market. Such educational initiatives will not only prepare individuals for employment in the hydrogen sector but also contribute to a broader public understanding of the benefits and safety of hydrogen technologies.

If the obstacles presented in this work are overcome, the development of the hydrogen sector in Poland will have a significant impact on the decarbonisation of the national economy and the technological progress of the country.

Appendix

Interview 1

Hydrogen Business Organisation (PL)
Hydrogen Valley Coordinator

Does European Hydrogen strategy set achievable objectives regarding hydrogen development in EU? What barriers do you identify in the face of these targets?

In my opinion, in the time horizon up to 2050, most of the objectives set are achievable. In terms of challenges there are couple of things which can be improved. One of the best improvements would be to adapt, to create a hydrogen regulatory package at European level, which every country could implement. This would lead to harmonisation of regulations, facilitate market coupling and the execution of international projects. Another problem is for sure financing. Hydrogen projects are expensive. Smaller companies lack the money for pilot projects and bigger - which could afford first pilot projects - need the money to fully commercialise these solutions.

What is your opinion about Polish Hydrogen Strategy?

I believe that in Poland we should start from the basics. We need a clear national definition what green hydrogen is, create decarbonization roadmap and commit to executing it no matter what current political turbulences are. That would provide stable market situation and facilitate the investments in the hydrogen sector.
More attention should be given to regional hydrogen polices which can be adjusted to the existing conditions in the area. In Pomerania, there is offshore wind and caverns, which could become such a green light industry basin. The south, for example, has post-mining areas, or even steelworks, which are there; they can also play a key role in the process of decarbonisation with the use of hydrogen. What is needed here, however, is a roadmap that shows which region offers what, and how and in what timeframe to exploit it. It's not about building whatever kind of installation you want; it's about using what's available at the lowest environmental cost to generate energy and then produce hydrogen and also meet local needs. Moreover, in the local strategies that you can recognise and consider critical points which if unaddressed sometimes can disrupt the execution of the entire transformation.

What funding options are available for hydrogen projects and what other actions should be taken in this regard?

In Poland, the main funding options for hydrogen projects are EU funds such as the National Reconstruction Plan and national funds such as from the National Centre for Research and Development. As we discussed those are not cheap projects and considering the scope of the decarbonization and hydrogen strategy targets more financial incentives should be introduced. Particularly on the part of local authorities and various types of tax relief. I also consider the European Hydrogen Bank to be a good initiative. However, in order to really assess its effectiveness, I think we still need some time, because this is already a fairly fresh topic.

Do you see the potential for a price reduction of green hydrogen in the future?

Of course. We simply need more RES generation sources. Automatically, if we increase the number of green megawatts, hydrogen will be cheaper. The second element is the situation that has been happening more and more in Poland recently, namely the disconnection of RES sources during periods of high production by the grid operator. This creates an opportunity for hydrogen generation and for this energy to be stored in hydrogen and then used. So, it is as if here we have full use of resources and opportunities that are now being wasted. When more generation sources are created, more electrolysers or other hydrogen production facilities are built, this price will come down.

Which sectors in Poland could benefit the most from hydrogen technologies?

There are many hydrogen technologies which can be implemented to decarbonise various branches of industry. Definitely operation of ports and large logistics centres. Another sector is heavy transportation which should be considered at multiple levels. Hydrogen solutions are better option for decarbonization of logistics areas over the battery systems due to better range, but also due to problems with efficiency, recycling, and environmental issues. Also, public transport like trains (PESA in Poland) or busses can implement hydrogen when electrification is not feasible. In addition, hydrogen may have a significant impact on the Polish heating sector, which is a significant industry due to its climatic location. In particular that we can safely blend hydrogen at a level of 10-15% in steam-gas units, and eventually even at 100%. Of course, at the moment we are not generating the necessary amount of hydrogen for this, but this could be a significant interim step on the road to full decarbonisation.

Do you think investments in blue hydrogen are beneficial for the development of the green hydrogen market?

In the short term, investments in blue hydrogen would be an aid for green hydrogen market development. It is known that due to the taxonomy and decarbonisation goals, blue hydrogen can only be considered as a transitional element, which would be phased out as the new RES and electrolysers capacity would be more developed.

What kind of investments are necessary for proper h2 market development? More electrolysers or h2 transmission infrastructure…?

There is a chicken and egg dilemma here. For the reason that, in order to spread at least hydrogen-based transport, we need stations. And without stations there will be no transport, so I think the first thing is to build a hydrogen filling station. It will involve a lot of technical and social dilemmas related to both land use, environmental permits and more but it would stimulate the development of the hydrogen sector the most.

Will Polish hydrogen be competitive with European hydrogen and hydrogen imported from other parts of the world?

I think you have to consider what is the environmental cost of producing hydrogen somewhere else and sending it to Poland over its price. The environmental cost of producing and transporting hydrogen needs to be thought through. The planned pipelines from Africa to Europe raise an environmental and ethical issues, using the resources of third world countries. The long-term perspective, points to the unsustainable exploitation of water resources. Without considering these issues, investments in hydrogen could lead to water scarcity in those foreign countries.

Interview 2

Environmental Agency
Scientific Associate

From your experience as an educator on energy transition and hydrogen technology, what obstacles do you face when educating and expanding public awareness of hydrogen?

People usually don't understand all the technical details. That is one issue which is quite common, that you are meeting two worlds. Like your world, which you try to communicate outside, is not the world that other people understand. So, you have
to bring all the complex matters down to a very simple and easily understandable way. Another case in terms of hydrogen is that we don't have a lot of "hands-on" experience and examples to show. You have a lot of theoretical PowerPoint presentations, and it is fine, but when it comes to what you can see with your own eyes - how does an electrolyser look? Or what's behind the logistics and the infrastructure needed for its production? You lack at the moment hands-on examples, where you can somehow experience hydrogen. That is something we are working on.

Have you encountered people with very strict opinions against current transition and hydrogen technologies?

Sometimes in rural areas, where people are not very familiar with new and modern technologies, you meet people who claim that they don't need this because they have been doing things differently for the last 80 years. They don't see the need for change because they believe that previous solutions worked well enough so why do they have
to change them? I don't need a solar park, I don't need a wind turbine in my backyard. Why should I care about the energy transition?
I think a good way to approach this attitude and convince those people is to show them on the one hand their benefits and on the other the importance of the problem. When they understand that the climate change is the global challenge, but climate action and energy transition done by the individual person can have a huge impact, maybe not on the whole world, but on their surroundings and local environment. Then people seem to be more open to new possibilities.

In your experience, is safety concern one of the problems that makes it difficult to gain public acceptance for hydrogen?

I wouldn't say it's a problem, but it's more like the natural interest of the people. They want to know how hydrogen works. If they still don't trust the technology, I will explain them in more detail that it's a safe technology if you know how to handle it. Usually, after such a conversation, they find hydrogen an interesting technology and do not see it as a problem. It's good when people ask questions and want to find out more.
Also transformation takes time, possibly spanning generations. But due to ongoing climate change we need quicker action. Convincing people of technology's benefits and illustrating the consequences of inaction are crucial for motivating change. The impacts of climate change are not distant threats, they will affect everyone. Once people understand this, they are more likely to commit to an energy transition.

Have you noticed that certain groups find it more difficult to accept hydrogen technologies? Looking at age, gender, ethnicity, education, or maybe national origin?

Not really. Rather it is a mixture of everything you mentioned.
Of course, for older people it is naturally harder for them to follow all the fast and new technical developments going on and sometimes to understand the importance of the ongoing change. But I

have also seen elderly people who are very concerned about the topic, who now think ahead in terms of what world are they going to leave for their children and grandchildren. Education matters a lot when it comes to young people.

We need to inspire them to get interested and involved in energy issues.

Education about hydrogen transition, as any other, needs honesty and transparency.

It is more effective when you are present among people, not online. I am involved in projects with different groups and when it comes to bigger h2 projects certain amount of friendship or trust between different groups/stakeholders is necessary. It is sad to see when everybody agrees that action should be taken but isn't due to political issues. Energy transformation is too big of a challenge to be overcome without international cooperation.

Interview 3

Industry
Junior Professional

As hydrogen valleys need to work with different stakeholders, such as the local community, regional authorities and companies, but also the government at national and international level, which of these actors should be focused on the most to develop an effective hydrogen valley?

The cooperation on different levels is needed for proper functioning of hydrogen valley. If I were to pick one, I think that the local level is the most important. It's hard to implement policy from a national level or European level if the local people do not accept the idea of hydrogen. What is it? Is it dangerous? Is it safe to use? Can I use it in my house already? When we answer those questions and get people and also local government on board, we can really start to make progress. Both national level and European level needs to be taken into consideration so the projects follow the bigger adapted strategy and can get extra funding opportunities. So, it's really important follow what kind of policy they're developing. For example, some new packages or you have the CBAM now, which of course influence the energy transition.

Do you think hydrogen valleys have the potential to improve national energy security in the short- and long-term?

In the short term, there are some barriers which needs to be overcome to state that hydrogen valleys improve energy security. First issue are raw and critical materials which are being used. We need a lot of them both to develop enough RES for hydrogen production and for implementation of hydrogen technologies. Even if hydrogen technologies don't need that much critical materials as battery storage it is necessary to look where from are we importing them and how safe those trade agreements are. Second issue is policy which at that moment is not supporting hydrogen sufficiently to enforce stable market conditions for investments. Companies who currently use fossil fuels needs to be more subsidized to switch to hydrogen as it is an expensive technology nowadays. This is the role of national governments and European Union.
Another issue connected to policy which I partially mentioned before is financing. Price of green hydrogen is too high for the final consumer. When hydrogen becomes accessible to people at the fair, low price and the value chain will be secured we can state that hydrogen valleys improve the energy security. In the long term however, energy security is a big argument for hydrogen so also hydrogen valleys. We have to switch to more sustainable energies to meet national and EU targets and hydrogen technology will have big part in achieving these goals.

How is the topic of importing hydrogen approached?

It is a very complex process with many stakeholders involved. First you need to find a country which is willing to export hydrogen. When you are agreeing on all the details like for example price and volume you look for the shipping options available and find your transporter. Next you need to find a port which is going to have a terminal which is capable of converting the hydrogen on the ship to your network. Finally, through your pipelines hydrogen can be delivered to your off-takers. Many people are involved at each step of this process. They not only need to succeed in signing beneficial agreements with their contractor but also communicate internally to assure that each step of the transportation is compatible with the previous and next one. The idea of hydrogen import form overseas to Europe is still quite but the work in this topic is progressing rapidly.

How would you address the problem of losses of imported hydrogen and estimated high price?

We will need to relay on both imported and domestically produced hydrogen. It is good in the way that we will diversify our energy needs in that way. Regarding the losses during transport of hydrogen, of course, it is an issue. Still, you have different ways to transport it like ammonia, liquefied hydrogen, compressed hydrogen, organic version of LOHC and more. Losses differ depending on the chosen solution, but it will be up to individual investors to pick the solution which is going to work best in their case. When it comes to price, I believe we will have to buy imported hydrogen simply because the demand for it in Europe is going to be too high to cover it locally.

What is your opinion on hydrogen imports to Europe and the associated controversy over environmental impact and increasing social inequalities?

Those topics are the first once that I think about when encountering import related projects. I always repeat that we need to follow sustainable development goals while pursuing this kind of projects. When it comes to water scarcity issues, we should focus on using sea water and after desalination use it to produce hydrogen. Hydrogen should never come before the local people water or energy needs.

Interview 4

Industry
Gas Market Expert

How would you describe the potential for future growth of the hydrogen market?

Nowadays hydrogen market consists of bilateral agreements between producers and consumers, and this situation is expected to continue in the short term. Development of the free hydrogen market is likely to happen in the mid/long term, around 2030. In order to achieve this goal, it is important that the process of market formation takes place together with all future market participants, market platforms and regulatory bodies.

What barriers do you see to the development of the hydrogen market?

The hydrogen market faces similar challenges as the development of the natural gas market faced more than 20 years ago. It is necessary to ensure proper regulatory and legal framework for the market. Missing entry-exit regime needs to be addressed. Flexibility so far is very low. Oligopolistic h2 market production - around 5 big suppliers controlling the market – is not benefiting it. There is also a need for storage. Ammonia can be used as the storage solution, using the technology of cracking to improve h2 flexibility, and in the long-term caverns storage can be implemented. To ramp up market development, shape of the market design should also be considered. Creating the body which would be place in between the user of the infrastructure (producer, consumer, mid-streamer (trader) and the infrastructure operator (grid, storage,…) would be beneficial - similar as TSO for electricity market or TSO/MAM (Market Area Manager) for the natural gas market today. Lastly product design has to be addressed. The quality of hydrogen needs to be standardized as nowadays it is being sold e.g. at different pressures and different levels of emissions are associated with its production. It may be interesting to explore the possibility of trading hydrogen regardless of colour, and separately trading certification of its origin.

Do you think that investments in blue hydrogen would benefit the market development?

There are pros and cons associated with the use of blue hydrogen. From a market perspective, the demand for hydrogen is there and in the short-term customers will need hydrogen regardless of colour. Investments in blue hydrogen could play the bigger or smaller role depending on the country. In some countries, like Germany, which have more restrictive regulations regarding blue hydrogen production, this may successfully discourage the investment in this type of h2. For other countries like the Netherlands, the opposite is true, blue hydrogen is subsidized and will support the H2 market ramp-up. I can imagine a European market based on both green and blue hydrogen, which would phase out blue hydrogen after 20-25 years when green hydrogen production is sufficient. However, we must bear in mind the price, which at the moment is much lower for blue hydrogen production and may discourage investment in new green hydrogen capacities.

From your perspective who holds the key to speeding up hydrogen market development?

In the last 5 years approximately 70-80% of missing political and regulatory framework (rules, directives, …) have been introduced. In my opinion now is the time for infrastructure bodies to create conditions which will ensure stable and reliable transmission and storage of hydrogen. Once achieved, it will improve market flexibility and encourage investments in the sector, which are necessary to drive hydrogen market development.

Interview 5

Regional Government
EU Funds Management

To what extent is the development of hydrogen technologies is supported by European Funds? What types of projects can apply for funding?

Priority I. European funds for smart growth

Innovative propulsion systems using hydrogen technologies belong to emerging industries, i.e. one of the Regional Intelligent Specialisations, therefore it will be possible to support R&D infrastructure dedicated to the development of these technologies in public research centres and in enterprises. It will be possible to support the conduct of research work with implementation in enterprises in the region. In the case of projects planned for implementation by research centres, the investments will have to go through the procedure of an opinion by the government party indicated in the Programme Contract.

Priority III. European Funds for sustainable mobility

Within the framework of the priority, it will be possible to support refuelling/powering stations for zero-emission buses as part of a larger project related to sustainable mobility (e.g. within the purchase of rolling stock or transfer centres). Hydrogen-based refuelling/power stations will be allowed. Support will also be given to the purchase of zero-emission electric/hydrogen bus fleets together with facilities for their servicing and maintenance.

Priority IV. European funds for efficient transport

It will be possible to finance charging infrastructure for electric and hydrogen vehicles as part of road projects. Additional scoring of such projects is foreseen.

Priority X. European funds for transformation

FST funds are planned to support the priority project entitled 'Centre for Renewable Energy Sources and Hydrogen Technologies in Rybnik'. The project envisages research into, among other things, energy transition, new alternative fuels, hydrogen technologies and energy management.
In addition, it will be possible to support investments contributing to the development of hydrogen technologies in SMEs - as part of the diversification of their activities. Large companies will be able to receive support for productive investments, but only under the condition that it is listed in the TPST.
As part of the operation of supported HUBs with FST funds, it will be possible to carry out activities on the development of, among other things, hydrogen technologies for entities located in supported HUBs.
In terms of support for sustainable mobility of a local nature, it will also be possible to invest in the purchase of a zero-emission hydrogen-based bus fleet with a station for its fuelling/refuelling.

Interview 6

Industry
Expert in Hydrogen Transport Sector

Which sectors do you think will be the first to implement hydrogen solutions?

The first area of the economy to rely on hydrogen will be transport. Transport as broadly defined public and long-distance transport. Here we already have the first implemented projects in serial production. We already have the infrastructure to refuel hydrogen vehicles, we have hydrogen vehicles, and we are developing various hydrogen combustion technologies to enable its use in different solutions.
Next will be the power industry and the metallurgy, where we have huge CO2 emissions, so this is a very good field for the hydrogen implementation. I also believe that after some time the first backyard hydrogen storage installations will also appear, with the ultimate aim of heating homes with hydrogen. In Poland, we already have the first project for an estate of detached houses, which are heated by combustion of hydrogen. So, I think these are the first industries that will develop, but definitely the leader in hydrogenisation at the moment is transport. Heavy transport, public transport. Based on my conversations with bus manufacturers, truck manufacturers, they already have the technology, and they are present in the hydrogen market.

What are the advantages of hydrogen over electrification in transport sector and why do you believe that hydrogen will develop their first?

In my opinion, there are three important reasons in favour of hydrogen in transport. The first, when it comes to long-distance transport.
Users expect that in the future, decarbonised vehicle - either electric or hydrogen (with internal combustion or with hydrogen fuel cell) will achieve similar ranges to a conventional diesel vehicle. So, we're talking about 800, even up to 1,000 kilometres. If we would like to achieve such a range in a battery vehicle, let's say a 40-tonne truck then it has to be equipped with 20 tonnes of batteries. This is totally unrealistic, economically unjustifiable, so long-distance transport will have to be based on hydrogen. In order to achieve this range in hydrogen vehicles, we are using an upgrade. City buses are usually designed for an operating pressure of 350 bar. Heavy-duty transport will be upgraded to 700 bar to store enough gas to enable that truck to travel those 800-1000 kilometres.
Another argument is the hydrogen refuelling time, which is much shorter than the battery charging time, even with fast charging. This is particularly important for the transport industry, where long charging intervals can generate costs for fleet maintenance. Battery production also requires large quantities of rare earth elements such as cobalt and lithium, which are resource-limited and also needed in other industries. The lack of effective substitutes for these raw materials creates challenges for future battery production. Thirdly, in the event of a mass shift to charging electric vehicles with large chargers, there would be a risk of overloading the power grid at times of high demand, and in contrast, hydrogen vehicles will be fuelled by hydrogen produced from RES surpluses power.

Do you see the potential for a decrease in the prices of hydrogen vehicles?

Although hydrogen vehicles are more efficient than current combustion cars (45-50% hydrogen fuel cell, diesel 30-35%, petrol even less), their price is much higher. The unit cost of producing an HFCV is relatively high, being approximately three times more expensive than a diesel vehicle and twice as expensive as a battery vehicle. This is largely because of the small scale of production. When production is scaled up to hundreds, thousands or millions, the cost structure will be significantly different. Currently, in Poland, the qualified cost of a hydrogen vehicle is approximately 90%, which indicates the necessity for governmental or European Union support for the development of this industry.

Do you see any other barriers that are slowing down the development of hydrogen in transport?

The fundamental problem is a dilemma: what came first, the egg or the chicken?
We have consulted with entrepreneurs and city officials. Why not invest in hydrogen cars? They can have hydrogen vehicles, but they ask the question: who will supply them with this hydrogen afterwards? Where is the infrastructure? I have asked others why there is no infrastructure. The reason is that there are no hydrogen vehicles. This is a chicken-and-egg dilemma. Fortunately, this is changing. The strengths of hydrogen are being recognised, and, with small steps, we are moving forward.
Another barrier is the price of hydrogen, which is currently around €12 per kilogram in the European Union, making it uncompetitive compared to fossil fuels. In order to stimulate demand, the price would have to fall to €4-5 per kilogram. The European Union has set up a Hydrogen Bank, which supports hydrogen production by offering subsidies. However, in order to produce the required volumes of green hydrogen, we need large investments in high-capacity electrolysers and surplus renewable energy which also entails considerable investment costs.

How does legislation and permitting process look like? Are there any areas that could be improved?

At present, there is a lack of coherent legislation, both at national and European level. There is a need for legislation on the production, distribution, and handling of hydrogen, and on the authorisation of applications in public road transport. In particular, for the construction of refuelling stations. The lack of clear legislation means that the institutions responsible for certification and regulation do not have clear guidelines, which lead to delays and an inconsistent approach in the authorisation process.
I understand, of course, that we are in a transitional phase, moving away from one technology and into another, but it would definitely be easier for everyone if there was consistent legislation covering the various aspects of hydrogen technology.

Given the lack of a distribution network to transport hydrogen, can we transport it efficiently and safely using hydrogen storage trucks?

The most efficient approach to the production of hydrogen is to do so in a distributed system, up to 200-250 km from the generation site. Currently, hydrogen storage tanks and containers are widely used as the main means of transporting hydrogen on a large scale. The containers, which are similar to those used to transport LPG, are subjected to appropriate certification and endurance testing to ensure safe transport. These containers are designed to be sectioned and have fire and overpressure protection. The transport of such containers is already commonplace, and their safety is ensured through testing and certification. There is no reason to believe that the transport of hydrogen is any more dangerous than the transport of gas or petrol. These solutions are already around us, and we do not even notice them. Therefore, despite the challenges, the current technology and legal framework for hydrogen transport offers the possibility of distributing hydrogen safely.

Who do you think holds the keys to the further development of the hydrogen market in the transport sector?

In my opinion, there is no clear message from the European Union that hydrogen is the solution we are choosing in Europe. Without this signal it is no wonder investors do not decide to take the risk and commit themselves fully to the development of hydrogen. Moreover, in hydrogen technology itself, we are not sure which technology will prevail in the long term. There are currently a number of propulsion options, including compressed hydrogen, liquid hydrogen, and ammonia, but the lack of certainty about the dominant technology by 2030 hinders investment and development in this field. It is also unclear whether other alternatives to hydrogen such as renewable natural gas will emerge. What is known is that vehicle manufacturers must make investment decisions that align with the European Union's expectations regarding the adoption of zero-emission vehicles. However, the lack of a clear dominant technology means that investment in battery vehicle development may be more profitable in the short term, which may delay the large-scale adoption of hydrogen vehicles. As such, the planned introduction of hydrogen vehicles in series is estimated to take place between 2028 and 2030.

Interview 7

Hydrogen Business Organisation (EU)
Hydrogen Regulatory & Market Intelligence

How do you assess the current state of the hydrogen market, looking at the entire value chain (production, distribution, and utilisation)?

Although they all work reasonably well, unfortunately they all work well in their own areas and there is no connection between them. This makes it hard to talk about the whole hydrogen economy for the time being. The problem, which is probably the main obstacle at the moment (outside of high production costs), preventing rapid development, is the lack of infrastructure. Due to the fact that investments are not interconnected, mainly small, local projects develop, and we do not reach the full potential of the market. Large-scale hydrogen production and its use will become fragmented in the future because of the dependence of the production on the RES availability. Without an infrastructure, to link different actors together, it will be difficult to have more than small pilot projects.

What other problems does hydrogen technology encounter nowadays and is it significantly developed?

In addition to infrastructure, legal issues are not yet at the relevant level. Another problem is also that when decarbonising large industrial facilities such as steel production - the demand for hydrogen is high. It is difficult to find favourable conditions and enough space for the required amount of RES to generate hundreds of thousands of tonnes of hydrogen needed. Of course, the price of hydrogen is not as low as we would like me to be, but this is a result of the lack of infrastructure and small-scale production. The price could be significantly lower.
Technical issues are often raised as a counterargument against hydrogen technology.
If I were to judge individually the degree of technical sophistication of the various industries, in my opinion, you can find areas in each of them that are already ready for full commercial implementation. When it comes to R&D, in a sense, there is still a lot of work to be done in every field. However, the lack of this research is no longer an obstacle at the moment. Of course, there will always be something to improve, something to enhance, but I do not see at the moment an area of the market where we cannot do anything because we do not yet know how to do it. We know everything, we know how to do everything. Now the issue is to implement it on a large scale, because in the small-scale everything costs “10 times more” than on a large scale.

At this point in time, is there sufficient pressure on the development of hydrogen technology in Europe to bring the technology to a level that meets its potential?

I don't know if this is a hydrogen pressure, but it is certainly a decarbonisation pressure. Different stakeholders have different perspectives on hydrogen and its role in different industries. It is fair to say that as far as heavy industry, aviation, and shipping are concerned, there is no dispute - due to the lack of other alternatives. The further we move towards lighter transport or heating; differences of opinion already start to emerge as to how we will decarbonise these sectors. So, I wouldn't say there is hydrogen pressure, but there is an awareness of that for sure, that without hydrogen these ambitious decarbonisation targets are not achievable. A 90% reduction in Co2 by 2040 might still be achievable with relatively little use of hydrogen but after 2040 these targets of minus 90% of Co2 emissions of carbon neutrality by 2050 are simply not technically possible without relying on hydrogen technology. The problem is to decide how and at what pace to develop this technology. You cannot wait to build infrastructure and storage facilities. You have to start building it 7-8 years earlier. And this is the biggest problem at the moment, to convince politicians that even though you do not need it today, if you are seriously committed to climate neutrality by 2050 or in 2040-90% reduction, even though you

do not need these storage facilities today, even though the network is not that necessary today, you have to start building it today because later it will be too late. This is where the problem is.
In principle, where there already is a demand for hydrogen, I think there is no disagreement on the need to develop green hydrogen. It is just a question of: at what pace, at what rate? We have not yet decided that hydrogen should be considered a priority.
I might also add that the new increased REPowerEU targets are not realistic in my opinion. The earlier targets of first 6GW of electrolysis and then 40GW by 2030 were relatively realistic. However, by wanting to rapidly reduce the share of natural gas in the mix, where hydrogen was seen as one of the main alternatives, the new target of 20 million tonnes of hydrogen consumed has created more harm to the hydrogen market than good. A target has been set in the public space and everyone knows it is impossible to achieve it, so no one takes it seriously, which inevitably affects the perception of the whole hydrogen sector.

How would you respond to the statement that large scale production of hydrogen will not have a significant impact on hydrogen price reduction? Due to for example high compression and cooling costs or other related costs needed for hydrogen production?

As far as alkaline electrolysers are concerned, we already have companies today in which electrolysers are used on a scale of even several hundred megawatts, only they are used to produce chlorine, not hydrogen. The technology is practically the same so I am not afraid that hydrogen production will not work on a larger scale. At the gigawatt scale however, we don't have the experience yet and certainly these projects will face new challenges.
We also have to remember that the electrolyser is only part of the equipment needed to produce hydrogen. The whole energy management model is important. The electrolysers that we have in the industry work in the baseload, and constant production is a different operation from variable load or part-load operation. In order to adapt production to variable RES, the timing correlation rules need to be improved. Under variable load operating regime, we don't know yet how the longevity or efficiency will look like. There are small-scale research projects, but again, if we are talking about 100, 200, 300 megawatts, we have yet to learn.
As far as the production costs of the electrolyser itself are concerned, I am 100% convinced that these costs will come down. If today, let's say, the total cost of a project is 2-3 thousand euros per kilowatt, then the electrolyser in this is a thousand. And the cost of the electrolyser will decrease, maybe even by 70-80%. In terms of the rest of the components, on the other hand, some of them like compressors and cooling systems are quite mature from a technological point of view, so it's hard to assume that anything will change in regard to them.
A lot of the costs, however, are contingency costs, because a lot of the equipment used to produce green hydrogen as well as its manufacturers have not been on the market long enough. All of this creates costs, risks and this is where these costs really swell. For this reason, I also believe that the price reduction potential of electrolysis is considerable.
It should also be borne in mind that CAPEX is about 20% of the cost of hydrogen generation. The rest is electricity costs. This is the main flywheel of the hydrogen economy. In the long term, RES costs are falling down, and, despite fluctuations, I see no obstacles to RES costs falling further in the long-term. Besides, there is pyrolysis, there is waste to hydrogen, there are quite a few of other methods to produce low carbon hydrogen, so I wouldn't worry about the supply part.

Do you see the development of blue hydrogen as a stimulant for the development of the hydrogen market or as a threat to the development of the green hydrogen market in the future?

The problem with blue hydrogen is that it is produced from natural gas. The infrastructure for gas is already there, so there is no reason to build blue hydrogen plants somewhere other than where the off take is. Since blue hydrogen will be produced where the offtake is, the hope that blue hydrogen will stimulate the construction of a hydrogen infrastructure may be flimsy.
From an industrial point of view, it may be a bit of competition for green hydrogen, but from the point

of view of using hydrogen as a fuel for transport or for the production of synthetic fuels, it may act more like a flywheel. As I mentioned green hydrogen in my opinion is going to get cheaper so I think after a period of time we will just phase out blue hydrogen because it will be less economically viable than green.
An important factor in determining the development of blue hydrogen is the legislation that is currently being developed to determine how the carbon footprint of low-emission hydrogen will be calculated. Although we do not know the details of the new legislation, we know that the emissions threshold is the same as for green hydrogen, which is 28.2 gCO2/MJ. If you look at these regulations that exist for renewable hydrogen and apply them to blue, with the same emission factors for natural gas, in terms of these upstream emissions, you see that blue hydrogen even with a very high capture rate - at 95% Co2, is just under the threshold of three tonnes of carbon per tonne of hydrogen. Just under the threshold. If additional requirements are added to the existing regulations, for example, monitoring hydrogen emissions -leakage, or even including other small, even minor emissions, this could be a very big barrier for blue hydrogen.
If it were to be used locally, right away where it is produced for industry, it would probably still be under the bar, but if it were to be compressed again, transported to cities to be used in buses, for example, it may not allow blue hydrogen to access the market at all, because of its high emissivity.
It also is important whether the upstream benchmark will be one for the whole of Europe or whether it will be calculated for each individual EU country taking into account where the gas comes from. Some countries take LNG from USA, for example, which is transported halfway around the world. If you calculate all of the emissions along the way, it doesn't matter if we capture 100% of the Co2, it still won't fit under the threshold. There are still a lot of unknowns, and we will see to what extent blue hydrogen will have a chance to emerge as a competitor to the low-carbon hydrogen market.

What is your opinion on retrofitting existing gas pipelines for the hydrogen use and what do you think about blending hydrogen with natural gas in existing infrastructure?

In my opinion, blending is a bit of a dead end.
To the extent that blending is possible without a lot of grid modification, about 5%, let's say, there are no obstacles.
On the other hand, I would certainly not recommend any investment to, all of a sudden, increase this 5% to 10%, or maybe to 15% and more. It is better to build already dedicated networks or retrofit existing natural gas networks, but for 100% hydrogen. One, it's more efficient, and two, as I mentioned, if it is profitable to produce hydrogen from natural gas, it is certainly not profitable to mix hydrogen back into the natural gas network. It's kind of like business-wise a completely abstract business. It's like having a product that is high value and mixing it with 95% of a lower value product. It doesn't make a lot of sense – without some kind of fa feed-in tariff subsidy scheme. And then the problem of extracting that hydrogen. Of course, there are methods to do that but it's expensive, especially if the hydrogen concentration is low. So, in my opinion it only makes sense in specific situations on the fringes of the economy. For example, to support decarbonization of the energy industry, when we produce hydrogen, and there is nothing to do with it locally, then ok, let's feed it into the grid. But then it's going to be burned together with natural gas, not taken back out of that grid for some other purpose. I don't mind blending, but I don't think that's the future of hydrogen.

What do you think hydrogen imports to Europe will look like? Will foreign production and imports be feasible at all, and if so, won't they compete with hydrogen produced in EU countries? What impact will this have on a just transition in African countries, for example?

The basic question is which energy pathway will be the most energy efficient and therefore the most feasible. For example, if the number of hours of sunshine is twice as great in Africa and the solar radiation per m^2 is also greater, then for obvious reasons compared to the same photovoltaic panel that stands in Europe the one in Africa will produce for longer and more. Of course, there are losses in transport because the hydrogen, once produced, has to be compressed, liquefied or used to produce ammonia or other hydrogen derivatives. Then it has to be transported by ship or gas pipelines over a long distance, which will certainly increase its price. In addition, for ammonia or other derivatives, you would have to crack it in Europe and get the hydrogen back, which involves further losses. So, in my opinion, imports will play a role, but to avoid these final losses it will be ammonia imports for the ammonia market or methanol imports for the methanol market - as finished products and not to reconverted to hydrogen and fed the internal EU hydrogen system.
When it comes to a just transition, the hydrogen market can contribute to it. The water shortage problem can be solved by desalinating seawater and using it to produce hydrogen. Looking at the cost of saltwater electrolysis, desalination is not a large part of the cost per kg of hydrogen produced, so I do not see any obstacles for part of the desalinated water to be even given back to the local community. In addition, we are not talking about behaviour like in colonial times where countries took cheap unprocessed raw materials to Europe. As I mentioned, we are talking about the production of ready-made products in these countries, such as ammonia, jet fuel or methanol. With this come new jobs for the local people and tax revenues for the economy. This relationship is more of a partnership, and I would sooner expect negative voices regarding this approach in Europe, where people may protest against European money being used to create jobs and investments abroad.

Interview 8

Industry
Hydrogen Technology Expert

What is your opinion on European Hydrogen Strategy? Are the goals achievable? How would you improve it?

In my opinion, as a document, European Hydrogen Strategy is good. I don't think that it needs any drastic improvements, because it is not really the true inhibitor of development hydrogen technology. I believe that it is relevant as a strategy document, setting the direction for the hydrogen economy. The only criticism or comment I can make it is that it is just a little over-ambitious about what hydrogen is and what it could be tomorrow, and what it will only be in 50- or 100-years' time. Some of the assumptions resemble more the political manifesto, created by people without the full knowledge about the mechanics of this market and limits of the technology.
The strategy document reflects well the objectives of the New Green Deal, i.e. emissions reduction, complementarity with the dynamic development of renewable energies, circular economy, local production, and an emphasis on energy security. These objectives are right in principle, but they do not hold up against technical reality in terms of the capabilities which hydrogen technology offers at the moment.
One of the things that I think is very good about EU Hydrogen Strategy is that it provides clear distinction between renewable, clean hydrogen and all the other forms of low-carbon hydrogen.

What do you think about Polish National Hydrogen Strategy?

When it comes to Polish National Hydrogen Strategy, I am highly critical of it. Flaws range from formal details concerning law making process (like referencing it to the other strategy which has already been repealed) to recognising the real purpose of hydrogen transition. It is not only just about the hydrogen but rather about the decarbonization process itself. Due to the lack of understanding of this principle, even a well-done part of the mapping of the large production market in Poland will not mean much in the future. As a result, large industrial companies are not being decarbonised in accordance with a deliberate strategy, leaving them dependent on emitting energy sources and all the associated costs. Moreover, some of the assumptions made in the strategy are simply unrealistic.
In my opinion Polish Hydrogen Strategy should be divided between the currently existing hydrogen market in Poland and new potential hydrogen market which is going to develop. Current market needs green hydrogen to substitute emissive hydrogen, which is being used as a technical gas, in refinery or during the production of fertilizers. This is the market which exists, that is actually operating. This market has real potential to invest and level the price difference between grey and blue hydrogen. The other market is something which is theoretically possible, which needs to be developed from scratch – example: use of hydrogen for heavy transportation. New market is the question of the future, it is hard to predict the trajectory of its development. Those markets are two completely different matters and there is no distinction between them at the strategy level. Additionally, within the already existing market we should ask what the future goals of the Polish economy are. Should we prioritise the use of hydrogen for the production of fertilisers, which will always be used, or for the operation of refineries, which will be phased out in line with decarbonisation targets?

What do you think about the future of hydrogen than?

When I look at the goals of European Union in terms of planned capacity of new RES I am much more optimistic. RES have the lowest marginal costs of power generation and idea to secure the leakage of green energy for electrolysis purposes, which will simply give presumably higher levels of return than the energy market itself – hydrogen

is the right thing to do.
The increase in power will be so gigantic that the price of energy will be extremely low, regardless of the level of tariffs introduced, therefore the incentive to use this energy for more profitable things, rather than selling it to the grid at ultra-low prices, will be high. Electrolysis will always be energy intensive. It is the huge amount of new renewable capacity that is being developed that will make hydrogen viable.

What are the myths about the use of hydrogen which you disagree with?

First common myth which I want to debunk is that the price of hydrogen will decrease significantly when the price of electrolysers will drop. It is simply not a case because electrolyser is only part of the apparatus used to produce hydrogen, which in general is not the most price relevant. Also, some technologies use too much critical material, so we cannot rely on them as much as we would like to. With high-volume production, yes, automation and increased demand is likely to translate into lower unit prices. However, we need to keep in mind issues that bigger electrolysers projects are having problems around the world. Electrolysers above 1 MW have issues with some parts, forcing downtime, and report a different performance than anticipated in the technical design. They encounter technical problems and without overcoming them, for now we can't talk about high-volume production and related with it potential for price drop.
I also do not believe that blending is the right approach to developing the hydrogen market in view of the problem of keeping the methane number of the final blend stable. Blending a few dozen percentage of hydrogen, in fact, has a negligible impact on emissions due to the volumetric difference of the gases, and requires a huge investment. The profit-to-cost ratio is simply unpromising. When you decide on 30% blending, you have to adapt the compressors to that, you have to adapt the pipe to that, and then in 10 years you decide that now it's 60% and you have to repeat that whole investment again. Let's say you produce hydrogen in high-purity electrolysis, and then you have to mix it with natural gas, actually dirtying it up. So why go through this huge technological effort at the beginning to bundle a renewable source with the production of hydrogen, in addition, to economically integrate it all, only to then pack it all into a pipe and burn it in a gas turbine. It can be even more fun when the end customer is sensitive and cannot take this hydrogen and has to filter it out for himself. This is becoming a joke. Economically, in the long run, if it is to be 100% ultimately, you have to invest in 100% straight away.

What is your opinion on transferring hydrogen as hydrogen derivatives, like ammonia on long distances?

When it comes to transferring hydrogen as derivatives, such as ammonia, there is a belief that converting hydrogen to ammonia can solve transport and delivery problems. However, there are challenges associated with ammonia production technology, which requires high load operation for most of the year. In addition, there is the need to provide a stable source of renewable energy throughout the investment period, which in turn generates astronomical costs. Attempts to use ammonia as a means of transporting hydrogen face high production costs and NOX and toxicity concerns. Alternatively, there is the topic of methanol, which also has its limitations, such as CO_2 emissions and complex feed-in processes. From a market development perspective, local production and consumption of hydrogen may be more economical than long-distance transmission. It is also important to take into account the differences in the cost of hydrogen production depending on location and power supply source, which affects the price of the final product.

Can blue hydrogen support the development of the hydrogen market or is it a brake on the development of the green market?

Blue hydrogen is a technology that has the potential to reduce emissions compared to traditional hydrogen production methods, but the storage of CO_2 is already causing some problems. There are concerns about the long-term sustainability of the storage technology due to the shifting of the CO2 problem to future generations and the need to expand the CO2 storage infrastructure. The cost of this expansion may burden the taxpayer, who is already burdened with financing the development of green technologies. Furthermore, uncertainty about the long-term availability and use of CO2 storage and other technologies such as caverns undermines the viability of blue hydrogen as a universal solution. The argument for blue hydrogen as a production source that is controllable can be achieved just as effectively with local sources of green hydrogen generation complemented by battery energy storage. Investments in blue hydrogen are only viable for companies operating in the natural gas market at the moment. They have lower production costs due to the use of infrastructure already in operation. Blue hydrogen is also the only option for them to stay in a market that is decarbonising. Therefore, despite the possibility of using blue hydrogen, there is a need to have a broad view of the development of the green hydrogen market, taking into account different scenarios and technologies.

Do you think that the development of the hydrogen market will create a large number of new jobs on the Polish market?

The development of the hydrogen market has the potential to create a significant number of jobs in the Polish market, but there are some doubts about the number of jobs needed. A number of companies in Poland already have technical staff with experience in the field of hydrogen-powered systems, suggesting that there is already a certain amount of skilled labour available. However, the actual demand for these skills is questionable, especially given the doubts about the pace of development of the hydrogen market. Consequently, there is a debate about whether to develop the skills of the workforce first for a market that may never emerge, or to invest in expanding the workforce when the market eventually does develop. However, from the point of view of industry professionals, it is recognised that people will be needed at every stage of the development of this industry, from design and designation to plant operation and so on. Therefore, the scope of work in this industry can be broad, encompassing not only technical competence, but also interpersonal and communication skills, which are important for public acceptance and safe operation of hydrogen technology. Here I can add that the aspect of social acceptance is generally lacking in Poland. No one knows what hydrogen is and no one has ever seen it, so everyone accepts it for the time being. We will see what happens when a refuelling station appears near the village, and someone comes and says that it could explode. Then we'll see if there is any public acceptance of hydrogen projects.

Interview 9

Industry
Alternative Fuels Expert

Do you believe that European Union Hydrogen Strategy is achievable in the timeframe suggested? What barriers to its implementation do you see?

The European Union's strategy is achievable as far as it goes, but it may not be possible to meet all the targets in the projected timeframe. From the point of view of the main objectives of hydrogen production, at 10 million tonnes in the EU and imports of a second 10 million tonnes, we are at a crucial stage. At the moment we have a number of projects in the European Union which are already after feasibility studies and after obtaining the financing. Whether these projects are finalised now depends on the consumers of hydrogen, i.e. the off takers. The main drawback or constraint that may cause these investments to be delayed is the demand factor for low emission hydrogen, which is heavily dependent on economics.
When the European strategy was created the cost of hydrogen production, according to initial predictions, was expected to fall. There were predictions, that in 2030, the cost of installing electrolysis capacity would fall by at least 50% compared to the baseline, which was in 2019-2020. However, today, after the COVID pandemic and the outbreak of war in Ukraine, costs and prices of materials have increased. This means that today, predictions from the latest consultancy reports indicate that investment costs in hydrogen production sources will increase rather than decrease.
Will the strategy's objectives succeed? That depends on this year and the beginning of next year. It is now that the key final investment decisions are being made, mainly on the part of the large industrial off-takers, who are responsible for the largest consumption of hydrogen and have a major impact on whether the strategy's objectives will be achieved.

What do you think of the measures the EU is implementing to address these challenges?

On the EU side, we have waited a long time for adequate regulation of the hydrogen market, and I believe that 2023 was a key year in which the European Union actually did its homework. The key legislative acts that should have been implemented were adopted. I mean for example RED 3 directive and or Refuel Aviation regulation which obliges all Member States. Failure to implement these acts may result in penalties being imposed. On the other hand, there are more support programmes such as the European Hydrogen Bank or programmes such as Connecting Europe Facilities. They help to develop the strategy's objectives but will not necessarily ensure the competitiveness of the industry. An example could be the production of fertilisers which, despite current support or even the introduction of CBAM, could easily be relocated outside the European Union due to still higher production costs than its emission-intensive foreign equivalents.

What is our opinion on the result of the first European Hydrogen Bank auction?

The aim of the Hydrogen Bank should be to close the gap between the production costs of grey hydrogen (around €2 per kg of hydrogen) and green hydrogen, which is more expensive at the moment. It is about €11/kg of hydrogen in Germany, €8/kg in Spain and slightly less in Portugal. After reviewing the materials of the winning projects published in the Hydrogen Bank auction, the difference between the price of hydrogen production in the corresponding country, even reduced by the amount of subsidy granted in the auction (maximum EUR 0.45/kg hydrogen) and the expected production costs should not be that significant. I still consider this to be one of the key barriers to hydrogen production for industrial purposes. The cost difference should and can be reduced through implementing "economies of scale" and the introduction of adequate support schemes depending on the location of the project.

What is our assessment of the Polish Hydrogen Strategy? What could be improved and what is done well?

I believe that the Polish Hydrogen Strategy is very well prepared and, in my opinion, today there is no time to update it. Instead of investing resources in the repetitive process of redeveloping strategy, consulting with stakeholders, and subsequently familiarising with the changes in the new strategy, it would be more beneficial to concentrate on achieving the aims of the current strategy.
More than a new strategy, we need an operational strategy to implement the current objectives. We know the targets of the strategy, but the focus should be on defining which actors are obliged to achieve these targets, launching new support programmes and transposing the RED3 directive to the national level. One potential avenue for further investigation is the issue of building a hydrogen transmission infrastructure, which is included in the current strategy. However, it is evident that without such a robust infrastructure to be constructed, it will be challenging to connect consumers with producers, and it should be stated who is responsible for its development. Normally, producers are more dispersed in locations favourable to the production of renewable energy and hydrogen. Currently, the consumer is an industry, and it is not feasible to relocate it in the near term. Transmission infrastructure therefore is very important for future functioning of the industry.

How would you assess the overall level of support programmes for the development of the hydrogen market on the national level?

There are several programmes that mainly support investments in development of hydrogen utilisation technology, more in the field of development projects. In my opinion, the most important programmes concerning support for large projects in the aforementioned infrastructure and large-scale production assets are still lacking. Without this, only small, dispersed projects will be implemented. They will certainly support the energy transmission sector because they will be invested in by RES producers, who are facing limitations from grid connections and would theoretically be a good supply of hydrogen for industry as well. However, large scale production is needed to meet industry demand. Under current conditions, we will achieve a large amount of investment but on a small scale. This will not have a positive impact on industry, which is significant for the Polish economy.

Why do you think some hydrogen valleys in Poland work better than others? What is the key to their success?

A popular definition is that a hydrogen valley is a local ecosystem that uses hydrogen in at least two areas of economy, for example, hydrogen generation with transport, industry, or energy. Such a basic definition indicates that hydrogen projects are to be implemented in this valley.
In Poland, also a slightly different model of hydrogen valleys has emerged. It takes form of associations that bring together a very large number of entities, such as universities, industry, business, local authorities, banks or other investors. This is a good model, the aim of which is to inspire and initiate hydrogen projects in the respective locations. Such expert meetings and discussions often lead to interesting initiatives on how to implement hydrogen into the local economy.
However, referring to those typical Hydrogen Valleys, whose current aim is to implement hydrogen, there couple of factors which needs to be taken in to account to ensure its efficient operation.
Currently have one internationally certified Hydrogen Valley in Poland - Amber Hydrogen Valley. It is an example of a very good use of the location. It has, one might even say, the best possible location for a hydrogen valley - in the proximity to the port, refinery, tri-city, airport, and a source of offshore wind generation. Another good practice is the ability to win additional funding. Amber Valley has applied for funding to the European Commission and there should be no problems in obtaining it. Another example is the Mazovian hydrogen valley. It brings together more than 40 entities and envisages the use of hydrogen in road transport (city buses and hydrogen refuelling stations) and at the airport (airport passenger buses or baggage transport vehicles). So, it is also important to find and create the right market for the hydrogen produced in the valley and cooperate with local authorities.

In the long term, the aim is for these valleys is to have hydrogen production and utilisation as part of their operation, so that eventually these small systems can be combined into a large hydrogen system. This would allow mutual business support, for example in trade of hydrogen and water, or the exchange of know-how between them, joining them to create national hydrogen market.

Interview 10

Industry
Hydrogen Project Manager

Does the Polish Hydrogen Strategy sufficiently support the development of hydrogen projects at the current market conditions? Do you think its objectives are well defined?

The Polish Hydrogen Strategy foresees the development and support of 6 sectors with targets for low-emission hydrogen production (refuelling stations, number of hydrogen buses, etc.). It is in line with the European Union's hydrogen strategy and decarbonisation policy. Hydrogen in sectors such as transport, energy, heating has been correctly identified. The establishment of business environment institutions to support the goals of hydrogen strategies and acquire funding has been successful, in the form of hydrogen valleys that are operational, but they bring mixed results.
The 2GW electrolysis capacity target is, in my view, at risk. Some projects have been abandoned at the planning stage due to a lack of funding or because the payback period is too long. Other projects in the pipeline are significantly delayed.

What are the reasons for the delays of the hydrogen projects currently under implementation?

Undoubtedly, the problem of unmatured PEM technology was an issue. In recent years, this technology has undergone a rather strong power scaling in terms of the systems offered by suppliers and now we are still suffering the consequences. At the moment we are talking about around 15MW of electrolysis in projects that are underway (are going to be implemented in the matter of time), and around 1 MW in completed projects.
What we hear repeatedly is that legislation has not kept pace with the development of technology and investors' desire to invest. In Poland, we are waiting for an amendment to the Energy Law and the implementation of the Hydrogen Act, which is basically a package of acts that the Hydrogen Act is supposed to implement. It is a lot of changes, because it involves not only the Energy Law, but also the Environmental Protection Act, or the Act on gaseous fuels, and so on. In recent years, from an environmental point of view, even the smallest installations have needed an environmental decision because the regulations were not fully adapted to the characteristics of hydrogen technology, which meant that, from an environmental point of view, they were often assigned to chemical technology of hydrogen production and so on. In principle, this is correct, but given the pro-environmental nature of these installations, the legislation should certainly be amended from this point of view. The procedure for obtaining an environmental permission decision should be simpler, because by entering into environmental impact assessment reports, prolong the investment by the few months, waiting for a final decision for a year and even more, which is a significant barrier.
Another problem is financing. We all know that hydrogen is a new technology which has high CAPEX to installed capacity ratio. In the last 2-3 years, there have actually been maybe two subsidy programs for such projects at the national level. We now hope for more new opportunities as a result of unblocking of the NRP for Poland by EU and the implementation of decarbonisation fund. At the moment, the techno-financial and the cost-benefit analyses show that even with a high subsidy of 50%, depending on the location, the intended consumers and so on, these installations are more or less profitable, but in principle, without extra funding, there is no question of an acceptable rate of return for the investors.

What is the current level of subsidies for hydrogen technologies and how can it change in the future?

A significant amount of funding comes from EU funds such as Important Projects of Common European Interest (IPCEI). This mechanism funds large structural projects, which means that smaller

investors have limited opportunities for support. In Poland, for example, Orlen has received significant funding for its hydrogen projects.
National funding often consists of the mix of EU funds and national funds such as the National Fund for Environmental Protection and Water Management (NFOŚiGW) or the National Centre for Research and Development (NCBR). Currently, projects are underway in the framework of the “hydrogenisation of the economy”, where funds are allocated for hydrogen vehicles, while transmission infrastructure or hydrogen production support programs are still awaited.

In which economic sectors do investors show the greatest interest in hydrogen technologies?

The main interest in hydrogen technologies is in the fuel and transport industries. Big actors in fuel industry have significant budgetary capacity, allowing hydrogen market to grow rapidly in this sector. An example of this is the development of hydrogen refuelling stations - several already exist and more are being procured and implemented, indicating a strong desire to decarbonise transport. Hydrogen in transport has great potential, especially as many Polish cities are planning to purchase hydrogen buses, funded by the National Fund for Environmental Protection and Water Management.
In the energy sector, particularly distributed energy, hydrogen is becoming increasingly popular as a means of energy storage. Problems with ageing power grids and difficulties in connecting photovoltaic installations are forcing the industry to look for alternative solutions. Hydrogen is starting to compete with battery systems.
Another important sector is the chemical industry, which is currently the largest consumer of hydrogen, mainly for the production of ammonia. Decarbonisation requirements and growing expectations from foreign partners for a low carbon footprint of products are forcing manufacturers to move towards green hydrogen and low emission hydrogen is strategic for the decarbonisation of this sector.

Why is hydrogen becoming attractive to investors in Poland despite its high cost? What factors are making hydrogen start to compete with batteries in the energy storage market?

Despite its high cost, hydrogen is becoming increasingly attractive to investors in Poland for several key reasons. Firstly, Poland has a long history and experience of using hydrogen in the petrochemical and chemical industries. Hydrogen is therefore not a new technology, which gives Poland an advantage in terms of expertise in the combustion, transfer and utilisation of hydrogen. This is in contrast to battery storage and electric cars, in which technologies Polish industry has never been very advanced. Investors are also attracted by the rapid development and falling prices of electrolyser technology, which makes hydrogen production more cost-effective. Hydrogen has a high energy density in bulk, which makes it competitive with battery storage, especially for long-term, high-power storage. Hydrogen also offers a wider range of applications than batteries - it can be used not only to generate electricity and heat, but also as a fuel for vehicles or for industry.
In the transport sector, hydrogen has an advantage over electric cars because of its longer range and faster refuelling time. This makes it an attractive option for decarbonising transport, especially in Poland, where the energy infrastructure is outdated and cannot cope with the fast-charging requirements for many electric vehicles. Hydrogen solutions provide an alternative to support underdeveloped electricity grids.
Investors are also recognising the potential of hydrogen in the context of energy diversification. Technologies such as biomass gasification, biogas reforming and the production of hydrogen from municipal waste can significantly increase the amount of hydrogen available, and Poland has great potential in utilising those production methods.

What features make one hydrogen valleys work better than the other?

Hydrogen valleys and clusters in Poland are organised in the form of associations and are financed either by membership fees of the association members or by external funding of the projects.

In the first years of operation, the capacity of these organisations is severely tested by the fact that obtaining public funding involves submitting applications, waiting for evaluation, signing contracts and so on. Often, the supporting partners, i.e. the companies, do not want to pay a high contribution fees, which is reflected in the budget of these valleys.
Valleys that have developed an attractive operating model and have invited companies that have a strategic interest in the valley have a chance of attracting funding from within. Often, however, they are simply based on small and medium-sized enterprises, and there are usually one, two or three strategic players who fund the majority of the valley's activities, typically for strategic, marketing or image-related reasons.
Once funding has been obtained and the stakeholders brought together, 'success' depends only on the effectiveness of the people or teams practically managing these valleys. It is the matter of initiating and proposing projects, creating initiatives to grow the business in this valley. These first two or three years in terms of organising funding strongly verify which valleys survive and thrive and which will remain only on paper.

How do you assess the level of expertise in hydrogen technology in Poland? Is there enough skilled workforce to achieve the goals outlined in the National Hydrogen Strategy?

From the point of view of the hydrogen refuelling stations business, Poland has a sufficient number of specialists, mainly thanks to the developed LPG and CNG sectors. Specialists in these fields can easily be retrained to work with hydrogen, so the maintenance and upkeep of refuelling stations will not be a problem.
The technology of fuel combustion in gas turbines or the use of fuel cells is very familiar to Polish power and heat engineers, and the implementation of hydrogen would only involve a change of fuel. For electrolysers, the situation is more complex and the number of available staff may be a problem. The operation and maintenance of electrolysers, even large ones, will be less challenging due to the automation of the systems, but still will require new, highly skilled personnel.
Educational programmes, particularly in vocational schools, will need to be adapted to meet the growing demands of hydrogen technology. Given the rapid growth of the sector and the increasing demand, it is expected that the number of training courses in hydrogen technologies will increase.

Interview 11

Academia
Research Coordinator

On the basis of your study, can you say whether the Polish hydrogen strategy is achievable? What obstacles to its implementation do you see?

The Polish Hydrogen Strategy is made up of individual elements and it is difficult to comment specifically on just one component. In general, it is already partially implemented, as hydrogen buses are already in operation and targets for hydrogen transport are being implemented. The strategy is being updated and at the moment we know that it will be implemented in in a similar shape as the current strategy, only the targets will be modified. Some targets will be more ambitious and some will be reduced or abandoned, taking into account the current state and prospects of the market.
Although the objectives of the strategy are clear, there is a lack of information on hydrogen at various levels of regulation. Many decisions on hydrogen projects are held up due to a lack of regulation because officials in the various institutions at the administrative level do not have the authority to interpret the regulations in a broader way, and the specific hydrogen law does not exist. Another issue identified in the study as a barrier to market development is funding, without which Polish firms will have a very difficult start in the European renewable hydrogen market.

Do you see the potential problem of lack of public awareness and acceptance in Poland as a threat to development for the development of the hydrogen market?

At the moment, there is not a great risk associated with the public acceptance of hydrogen, because the first association with hydrogen is a lack of association.
First of all, people do not know what it is. When asked, some people said that they remember it as a chemical element. In other words, basic knowledge from primary school, because later on people do not learn much about hydrogen. A very small percentage of people know something about hydrogen technology, and even fewer associated hydrogen with energy. In general, there is a very low percentage of knowledge, very low awareness. Comparing these surveys to similar ones in Germany, we see significantly greater variation over there. Perhaps hydrogen technology is not widely known there either, but there was greater awareness of the various innovations in energy technology. In our study, after using the anchoring method with simple, neutral information for the respondents (about 7 sentences like: hydrogen can be used as a fuel, it is an energy carrier that has its positives and negatives) people's first impression was positive. They associated it with RES, for which the level of public acceptance in Poland is growing. Regarding hydrogen, as with other RES technologies, respondents were generally 'in favour', but did not want to be additionally burdened with the costs of the energy transition. So, there is a lot of acceptance in terms of the very idea of implementation, just "let someone else pay for it - preferably the European Union". People also rated hydrogen as a very expensive energy carrier.
It is an interesting phenomenon that, without a lot of knowledge about hydrogen production, about storage and its value chain, Poles with a low understanding of energy issues, know, that it will certainly not be cheap solution. And there is immediate resistance to this because nobody wants to pay for it. It's interesting to compare it with Germany, because in Germany, the German public is being prepared a little bit

for this change, for example to replace LPG by a mixture of LPG and hydrogen and so on.
In Poland, on the other hand, it is more a question of greater acceptance in terms of hydrogen use in heavy transport or buses for example. And here we can see small but positive trends towards social acceptance. People who ride public transport are more aware when it comes to buses and also hydrogen transport. And this is a bit of a half-joke, but it seems that these mini advertisements in buses are fulfilling their role and educating.
Another conclusion we drew from the survey is that the explosive nature of hydrogen and the potential restrictions on the use of hydrogen vehicles and equipment could be some kind of flashpoint in the future. Especially at a time when some are keen to spread fake news and myths, destabilising the situation in Poland. For the moment, however, public acceptance of hydrogen is quite positive.
In our research we also found a greater suspicion towards hydrogen when information communication was based only on positive aspects or based on sovereignty by referring to hydrogen as "Polish hydrogen". In the first case, this was interpreted as manipulation, irrespective of the education or age of the study group. In the second case, this generated scepticism and reluctance about referring to hydrogen as 'Polish'. Hydrogen was interpreted like the sun or the wind - nobody's property. Information about the risks was important to expand people’s knowledge and enable them to form an opinion about hydrogen technology.
The survey also found that 74% of respondents would like to learn more about new ways of generating electricity. Almost ¾ of Poles need and want information in this area.
As far as sources of knowledge are concerned, the majority identified communication from experts, scientists as a reliable source and about half would like to receive information from traditional media (in a pool not divided by age).

How would you rate the level of hydrogen education, particularly in terms of technical schools?

There is a significant gap in education about hydrogen technology at technical school level. Educating enough engineers and specialists at managerial level is important, but it is equally important to prepare technicians which would allow for the daily operation and maintenance of hydrogen systems. We see the first steps in this direction - for example, in the technical high school at the Oil and Gas Institute in Krosno and in some technical schools in Greater Poland, where the curricula are being modified for hydrogen technology.
Teachers and students have to adapt to these changes, which often requires additional training for teaching staff and the provision of appropriate educational materials.
To support this process, for example, the 'Pop H2 Society' project was introduced, which aims to popularise knowledge about hydrogen. The project creates lesson plans, educational videos and organises webinars to help raise the awareness and competence in hydrogen technologies among both teachers and students.

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